AN AMERICAN TEXT-BOOK

OF

PHYSIOLOGY

BY

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PREFACE.

THE collaboration of several teachers in the preparation of an elementary text-book of physiology is unusual, the almost invariable rule heretofore having been for a single author to write the entire book. It does not seem desirable to attempt a discussion of the relative merits and demerits of the two plans, since the method of collaboration is untried in the teaching of physiology, and there is therefore no basis for a satisfactory comparison. It is a fact, however, that many teachers of physiology in this country have not been altogether satisfied with the text-books at their disposal. Some of the more successful older books have not kept pace with the rapid changes in modern physiology, while few, if any, of the newer books have been uniformly satisfactory in their treatment of all parts of this many-sided science. Indeed, the literature of experimental physiology is so great that it would seem to be almost impossible for any one teacher to keep thoroughly informed on all topics. This fact undoubtedly accounts for some of the defects of our present text-books, and it is hoped that one of the advantages derived from the collaboration method is that, owing to the less voluminous literature to be consulted, each author has been enabled to base his elementary account upon a comprehensive knowledge of the part of the subject assigned to him. Those who are acquainted with the difficulty of making a satisfactory elementary presentation of the complex and oftentimes unsettled questions of physiology must agree that authoritative statements and generalizations, such as are frequently necessary in text-books if they are to leave any impression at all upon the student, are usually trustworthy in proportion to the fulness of information possessed by the writer.

Perhaps the most important advantage which may be expected to follow the use of the collaboration method is that the student gains thereby the point of view of a number of teachers. In a measure he reaps the same benefit as would be obtained by following courses of instruction under different teachers. The different standpoints assumed, and the differences in emphasis laid upon the various lines of procedure, chemical, physical, and anatomical, should give the student a better insight into the methods of the science as it exists

book will be found useful to many practitioners of medicine who may wish to keep themselves in touch with the development of modern physiology. For this class of readers references to literature are not only valuable, but frequently essential, since the limits of a text-book forbid an exhaustive discussion of many points of interest concerning which fuller information may be desired.

The numerous additions which are constantly being made to the literature of physiology and the closely related sciences make it a matter of difficulty to escape errors of statement in any elementary treatment of the subject. It cannot be hoped that this book will be found entirely free from defects of this character, but an earnest effort has been made to render it a reliable repository of the important facts and principles of physiology, and, moreover, to embody in it, so far as possible, the recent discoveries and tendencies which have so characterized the history of this science within the last few years.

CONTENTS OF VOLUME I.

those of the amœba.[1] The property of contractility is possessed by a vast variety of unicellular structures in lower forms of animal life. Another example is the Vorticella (Fig. 2).

The vorticella, like the amœba, is a little animal which, although consisting of a single cell, possesses within its microscopic form all the physiological properties essential to life and the perpetuation of its species. It consists of a bell, with ciliated margin, borne upon a contractile stalk. If touched with a hair, or jarred, the cell rapidly contracts; the edge of the bell is drawn in so as to make the body nearly spherical, and the stalk is thrown into a spiral and drags the body back toward the point of attachment. The contraction is rapid; the relaxation, which comes when the irritation ceases, is gradual. An interesting account of the movements of *Vorticella gracilis* is given by Hodge and Aikins[2] under the title of "The Daily Life of a Protozoan."

Other examples of contractile power possessed by apparently simple organisms are to be found in the tentacles of Actiniæ, the surface sarcode of sponges, the chromatoblasts of Pleuronectidæ,[3] which are controlled by nerves and under the influence of light and darkness change their size and so alter the color of the skin, and the vast variety of ciliated forms, including spermatozoa, and some of the cells of mucous membranes.[4]

Irritability.—We have thus far referred to but one of the vital properties of protoplasm, viz. contractility. Another property intimately associated with it is *irritability*. Irritability is the property of living protoplasm which causes it to undergo characteristic chemical and physical changes when subjected to certain external influences called irritants. Muscle protoplasm is very irritable, and is easily excited to contraction by such irritants as electric shocks, mechanical blows, etc. The muscles which move the bones rarely, if ever, in a normal condition, exhibit spontaneous alterations in form, and cannot be said to possess automatic power. By *automatism* is meant that property of cell-protoplasm which enables it to become active as a result of changes which originate within itself, and independently of any external irritant. Examples of this power may perhaps be found in the movements of ciliated organisms and the infusoria. Possibly the rhythmic movements of heart muscle are of this nature. Still another property of protoplasm, closely allied to contractility and irritability, and possessed by muscle-substance, is conductivity.

Conductivity is the property which enables a substance, when excited in one part, to transmit the condition of activity throughout the irritable material. For example, an external influence capable of exciting an irritable muscle-fibre to contraction, although it may directly affect only a small part of the fibre, may indirectly influence the whole, because the condition of activity which it excites at the point of application is transmitted by the muscle-substance throughout the extent of the fibre.

[1] An excellent description of these movements, accompanied by illustrations, is given in *Quain's Anatomy*, vol. i., pt. 2, pp. 174-179.

[2] Hodge and Aikins: *American Journal of Psychology*, 1895, vol. vi., No. 4, p. 524.

[3] Krukenberg: *Vergleichend-physiologische Vorträge*, 1886, Bd. i. S. 274.

[4] A careful study of the different forms of movement exhibited by simple organisms has been made by Engelmann: *Hermann's Handbuch der Physiologie*, 1879, Bd. i., Th. 1, S. 344.

does not prevent it from being classed with other irritable forms of living cell-substance as protoplasm. In spite of differences in structure and composition, nerve protoplasm and muscle protoplasm are found to have many points of resemblance. An explanation of the physiological resemblances may be found in their common ancestry. All the cells of the many structures of the animal body are descended from the two parent cells from which the animal is developed. The fertilized ovum divides, and two cells are formed, these new cells divide, and so the process continues, the developing cells through unknown causes becoming arranged to form more or less definite layers and groups, which by means of foldings and unequal growths develop into the various structures and organs of the fetus. At the same time that the division is going on, the total amount of material is increasing. Each of the cells absorbs and assimilates dead food-material, and this dead material is built into living substance. During this process of development and growth the cells of special tissues and organs acquire special anatomical and chemical characters. This development of specialized cells is termed cell-differentiation. Hand in hand with the anatomical and chemical differentiation goes a physiological differentiation. The protoplasm of each type of cell, while retaining the general characteristics of protoplasm, has certain physiological properties developed to a marked degree and other properties but little developed, or altogether lacking. The fertilized ovum does not have all the anatomical and chemical characteristics of all the cells which are descended from it, not at least in just the form in which they are possessed by these cells, and it cannot be assumed that its living substance possesses all the physiological properties which are owned by its descendants. Many of these properties it must have, for many of them are essential to the continuance of life of all active cells,—such as the power to take in, alter, and utilize materials which are suitable for the building up and repair of the cell-substance, the power of chemically changing materials possessing potential energy so that the form of actual energy which is essential to the performance of the work of the cell shall be liberated, and the power to give off the waste materials which result from chemical changes. The protoplasm of the ovum, to have these powers, has properties closely allied to absorption, digestion, assimilation, respiration, excretion ; and, in consideration of the special function of the ovum, we may add that it possesses the property of reproduction. The question of its possessing the characteristic properties of muscle and nerve protoplasm cannot be answered off-hand. Careful study, however, has shown the ovum of Hydra to possess irritability, conductivity, and contractility. It undergoes amœboid movements, as was first shown by Kleinenberg. Balfour,[1] in writing of the development of the ova of Tubularidæ, which is of a type similar to Hydra, says: "The mode of nutrition of the ovum may be very instructively studied in this type. The process is one of actual feeding, much as an amœba might feed on other organisms." Something similar seems to be true of the ova of echinodermata. During impregnation various movements are described implying the properties of irritability, conductivity, and contractility. Thus in the case of *Asterias glacialis*, when the head of the

[1] *Comparative Embryology*, pp. 17, 29.

be able to accurately measure them. This we cannot do. We are unable to state in irritation-units the relative value of different kinds of irritants. Even if we could accurately estimate the amount of energy which each form of irritant can expend in iritation, we should have only one of the many factors which determine its efficiency. It is equally difficult to compare the irritating effect of irritants upon different forms of protoplasm; *e. g.* we cannot state what degree of activity of a nerve-fibre corresponds to a certain amount of activity in a muscle-fibre. In spite of the lack of exact quantitative measurements, we have gained a clear idea of the way different forms of irritants act when applied to nerves and muscles in certain ways, and have learned to control the methods of excitation sufficiently to permit the influences which alter the irritability of nerves and muscles to show themselves. The effect of irritants can best be studied upon the nerves and muscles of cold-blooded animals, because these retain their vitality and irritability for a considerable time after they have been separated from the rest of the body. It is a common observation of country folk that the body of a snake remains alive for a long time after the head has been crushed, while the body of a chicken loses all signs of life in a comparatively short time after it has been decapitated. More careful examination would show that in neither case do all parts of the body die simultaneously. Each of the myriad cells has a life of its own, which it loses sooner or later according to its nature and to the alterations to which it is subjected by the fatal change. The cells of cold-blooded animals, as the snake and frog, are much more resistant than those of warm-blooded animals, because the vital processes within the cells are less active, and the chemical changes which precede and lead to the death of the part occur more slowly. For instance, the nerves and muscles of a frog remain irritable for many hours, or even days, after the animal has been killed and they have been removed from the body. This fact is of the greatest use to the student. It enables him to study the nerve or muscle by itself, and under such artificial conditions as he cares to employ. Experience shows that the facts learned from the study of the isolated nerve and muscle hold good, with but slight modification, for the nerves and muscles when in the normal body. Moreover, it has been found that the nerves and muscles of warm-blooded animals, and even man, resemble physiologically as well as anatomically those of the frog. The correspondence is by no means complete, but it is so great as to make the facts discovered by a study of the nerves and muscles of the frog of the utmost importance to us. We are driven to such sources of information because of the great difficulty of keeping the muscles of warm-blooded animals alive and in a normal condition after removal from the circulation.

Irritability of Nerves.—The following preparation suffices to illustrate the more striking effects of irritants upon a nerve. A frog is rapidly killed, and then the sciatic nerve is cut high up in the thigh and dissected out from its groove, the branches going to the thigh-muscles being divided. The leg is then cut through just above the knee. This gives a preparation consisting of the uninjured lower leg and foot, and the carefully prepared nerve supplying the muscles of these parts. The leg may be placed foot upward, and fastened

time shows, first, that the muscle protoplasm can be irritated directly, and secondly, that the nerves do not communicate directly with the muscles, but stimulate them through the agency of terminal end-organs, called *motor end-plates.*[1]

Curare Experiment.—Rapidly destroy the brain of a frog with a slightly curved, blunt needle, and, to prevent hemorrhage, plug the wound by thrusting a pointed match through the foramen magnum into the brain-cavity. Expose the sciatic nerve of the left thigh, carefully pass a ligature under it, and tie the ligature tightly about all the tissues of the thigh excepting the nerve, thus cutting off the circulation from all the leg below the ligature without injury to the nerve. Inject into the dorsal lymph-sac or the abdominal cavity a few drops of a 2 per cent. solution of curare. In from twenty to forty minutes the drug will have reached the general circulation and produced its effect.

Although the brain has been destroyed and the frog is incapable of having sensation, it will be found that muscular movements will be made if the skin be pinched soon after the drug has been given. These are reflex movements, and are due to excitation of the spinal cord by the nerves connected with the skin. As the paralyzing action of the drug progresses, these reflex actions become feebler and feebler until altogether lost in the parts exposed to the drug, although they may still be shown by the parts from which the drug has been excluded. The condition of the nerves and muscles can be examined as soon as reflex movements of the poisoned parts cease.

To ascertain the action of the poison, expose the nerves of the two legs, either high up in the thigh or inside the abdominal cavity, where they have been subjected to the poison, and test their irritability by exciting them with electric shocks. Stimulation of the motor nerve of the right leg (*a*, Fig. 4) causes no contraction of the muscles of that leg, while stimulation of the motor nerve of the left leg (*b*), results in active movements of the muscles of that leg. The response of the left leg shows that nerve-trunks are not injured by the poison, and that the paralysis of the right leg must find some other explanation. On testing the muscles it is found that they are irritable and contract when directly stimulated. Since neither nerve-trunks nor muscles are poisoned, it is necessary to assume that the cause of the paralysis is something which prevents the nerve-impulse from passing from the nerve to the muscle. Microscopic examination shows that the nerve-fibre does not communicate directly with the muscle-fibre, but ends inside the sarcolemma in an organ which is called the motor end-plate (see Fig. 31). It appears that the nerve acts on the muscle through this organ, and its failure to act on the side which was exposed to the curare was because the end-plate had been paralyzed by the drug. By the use of curare, therefore, we are enabled to prevent the nerve-impulse from reaching the muscles, and, when we have done this, we find that the muscle is still able to respond to direct excitation with all forms of irritants, viz.,

[1] Ch. Bernard: "Analyse physiologique des Propriétés des Systèmes musculaires et nerveux au moyen du Curare," *Comptes-rendus*, 1856, p. 825. Kölliker: "Physiologische Untersuchungen über den Wirkungen einiger Gifte," *Archiv für pathologische Anatomie*, 1856.

CONDITIONS WHICH DETERMINE THE EFFECT OF EXCITATION.

The result of the irritation of nerve and muscle is dependent on two sets of conditions—namely, conditions which determine the irritability; conditions which determine the efficiency of the irritant.

It will be necessary for us to study the second set of conditions first—for, before we can judge of the irritability and the effect of various influences upon it, we must consider how far the activity of the nerve and muscle is dependent on the character, strength, and method of application of the irritant.

Conditions which Determine the Efficiency of Irritants.—Some of these conditions can be best studied on nerves, while others are more apparent in their effects on muscles. The most useful irritant for purposes of study is the electric current. Mechanical, thermal, and chemical irritants are likely to injure the tissue, and are not manageable, whereas electricity, if not too strong, can be applied again and again without producing any permanent alteration, and can be accurately graded as to strength, place, time, duration of application, etc. Of course, the results obtained by the use of a given irritant cannot be accepted for others until verified. The conditions which determine the effectiveness of the electric current as an irritant may be classed as follows: (*a*) The rate at which the intensity changes. (*b*) The strength of current. (*c*) The density of current. (*d*) The duration of application. (*e*) The angle of application. (*f*) The direction of flow.

Irritating Effect of the Electric Current.—Luigi Galvani, Professor of Physics at Bologna, 1791 (or, according to some, his wife Lucia), observed the legs of frogs which had been prepared for the kitchen, and had been suspended by brass hooks from an iron balcony, make convulsive movements every time the wind blew them against the iron. He repeated the experiment in his laboratory, and decided that the frogs had been excited to action by electric currents developed within themselves; he looked upon the metals which he had used merely as conductors for this current. Volta, Professor of Natural Philosophy at Pavia, repeated Galvani's experiment, and concluded that there had been an electric current developed from the contact of the dissimilar metals with the moist tissues of the frog. In accordance with this idea he constructed the voltaic pile, and this was the starting-point of the science of electricity of to-day.

Although it is true that, under certain conditions, differences in electric potential sufficient to excite muscles to contraction can be developed in the animal body, the contractions of the frog's leg which Galvani observed were due to the metals which he employed. The experiment can be easily performed by connecting a bit of zinc to a piece of curved copper wire, and bringing the two ends of the arc against the moist nerve and muscle of a frog. A stronger and more efficient shock can be obtained from a Daniell or some other voltaic cell.

A *Daniell cell* (Fig. 5) is composed of a zinc and copper plate, the former dipping into dilute sulphuric acid, the latter into a strong copper-sulphate solution. Although gravity will keep these liquids separated, if the cell is to be moved about it is better

Keys.—It is not as convenient to stimulate a nerve by touching it with the electrodes as it is to place it upon the electrodes and close the connection between the zinc and copper at some other part of the circuit; this may be done by what is called a key. Any mechanism which can be used to complete the circuit could receive this name, and there are a number of convenient forms. The one most used by physiologists is that devised by Du Bois-Reymond, and which bears his name (see Fig. 7). This has the advantage of being capable of being used in two different ways—one simply as a means to close the circuit, and the other to short-circuit the current. These two methods are shown in Figure 8.

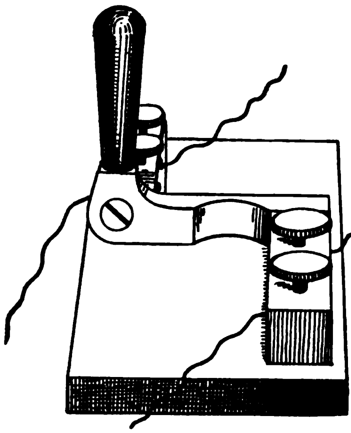


FIG. 7.—Electric key.

By the former method the key supplies a movable piece of metal by which contact between the two ends of the wires may be made as in *a* (Fig. 8), or broken as in *b*, and the current be sent through the nerve, or prevented from entering it. By the latter method the battery is all the time connected with the electrodes, and the key acts as a movable bridge between the wires, and when closed gives a path of slight resistance by which the current can return to the battery without passing through the nerve. The current always takes the path of least resistance, and so, if the key be closed as in *c*, all the current will pass through the key and none will go to the nerve, which has a high resistance, whereas if the key be opened as in *d*, the bridge being removed, all the current will go through the nerve. It is often better to let the cell or battery work a short time and to get its full strength before letting the current enter the nerve, and the short-circuiting key permits of this. Moreover, there are times when a nerve may be stimulated if connected

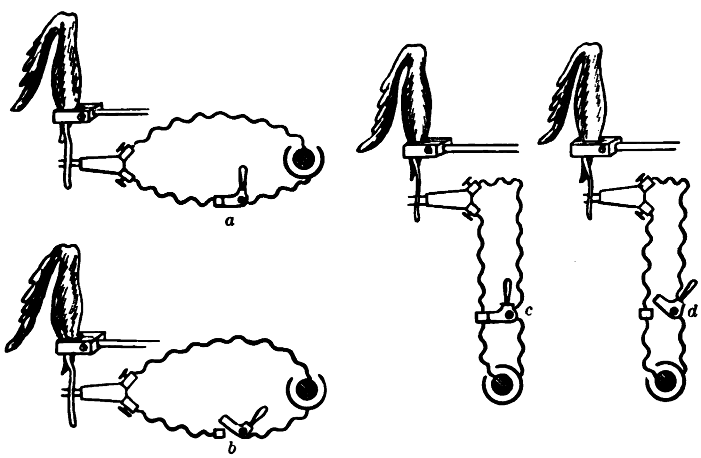


FIG. 8.—Electric circuiting.

with the source of electricity by only one wire; when the nerve is so excited, it is called unipolar stimulation; this may be prevented by the short-circuiting key.

As has been said, a nerve is irritated if it be connected with a battery and an electric current suddenly passes through it. Unless the current be very strong the irritation is transient, however; the muscle connected with the

containing the nerve. The wires from the battery are connected with binding-posts, *a*, *b* (Fig. 9), at opposite sides of a circular groove containing a saturated solution of zinc sulphate. Strips of amalgamated zinc connect the binding-posts with the fluid, and so complete a circuit which offers much resistance to the passage of the current. From the centre of the block containing the groove rises an upright bearing a movable horizontal bar, from each extremity of which an amalgamated zinc rod, *e* and *f*, descends and dips into the zinc-sulphate solution. The zinc rods are connected with binding-posts on the movable bar, and from these wires pass to the electrodes on which the nerve rests. The bar revolves on a pivot on the top of the upright, and thus the zinc rods can be readily approached to or removed from the zinc strips, the poles of the battery. When the zinc rods hold a position midway between these poles, the current all passes by the way of the fluid. As the bar is turned, so as to bring the zinc rods nearer and nearer the two poles of the battery, the current divides, and more and more of it passes through the path of lessening resistance of which the nerve is a part. When the zinc rods are brought directly opposite the poles of the battery nearly all the current passes by the way of the nerve. If the bar be turned more or less rapidly, the current is thrown into, or withdrawn from, the nerve more or less quickly.

By this arrangement we can not only observe that the nerve fails to be irritated when the current is made to enter or leave it gradually, and when it is flowing continuously through it, but that sudden variations in the density of the current flowing through the nerve, such as are caused by quick movements of the bar, although they do not make or break the circuit, serve to excite. This experiment shows that electricity, as such, does not irritate a nerve, but that a sudden change in the density of the current, whether it be an increase or decrease, produces an alteration in the nerve-protoplasm which excites it to action and causes the development of what we call the nerve-impulse.

Du Bois-Reymond's Law.—Du Bois-Reymond formulated the following rule for the irritation of nerves by the electrical current: "It is not the absolute value of the current at each instant to which the motor nerve replies by a contraction of its muscle, but the alteration of this value from one moment to another; and, indeed, the excitation to movement which results from this change is greater the more rapidly it occurs by equal amounts, or the greater it is in a given time."

We shall have occasion to see that this rule has exceptions, or rather that there is an upper as well as lower limit to the rate of change of density of the electric current which is favorable to irritation.

Similar observations may be made with other forms of irritants. Pressure, if brought to bear on a nerve gradually enough, may be increased to the point of crushing it without causing sufficient irritation to excite the attached muscle to contract, although, as has been said, a very slight tap is capable of stimulating a nerve. Temperature, and various chemicals, likewise, must be so applied as to produce rapid alterations in the nerve-protoplasm in order to act as irritants. The same rule would seem to hold good for the nerve-cells of the central nervous system. It is a matter of daily experience that the nervous mechanisms through which sensory impressions are perceived are vigorously excited by sudden alterations in the intensity of stimuli reaching them, and but little affected by their continuous application; the withdrawal of light, a sudden

fall of the density of the current in the secondary coil is very rapid, and this rapid double change in density of the current causes the induction shock to be a very effective irritant. The breaking induction shock, as we call that which is produced by breaking the primary current, is found to act more vigorously than the making shock, which is the reverse of what is found with direct battery currents. The cause of this lies in the nature of the apparatus. At the moment that the current begins to flow into the primary coil, it induces not only a current in the secondary coil, but also currents in the coils of wire of the primary coil. These extra induced currents in the primary coil have the opposite direction to the battery current and tend to oppose its entrance, and thereby to prevent it from immediately gaining its full intensity. This delay affects the development of the induced current in the secondary coil, causing it to be weaker and to have a slower rise and fall of intensity than would otherwise be the case. When the primary current is broken, on the other hand, there is no opposition to its cessation, and the current induced in the secondary coil is intense and has a rapid rise and fall. These differences are illustrated in Figure 12.

Myogram.—To accurately test the effect of the making and breaking induction shocks, it is necessary to record the reaction of the nerve; this can be done by recording the extent to which the corresponding muscle contracts in response to the stimulus which it receives from the nerve. In such an experiment it is customary to use what is known as a nerve-muscle preparation. The gastrocnemius muscle and sciatic nerve of a frog, for instance, are carefully dissected out, the attachment of the muscle to the femur being preserved, and the bone being cut through at such a point that a sufficiently long piece of it shall be left to fasten in a clamp, and so support the muscle (see Fig. 13).

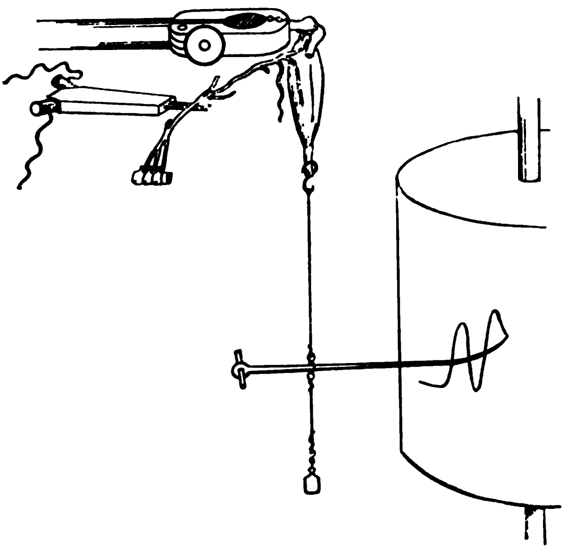
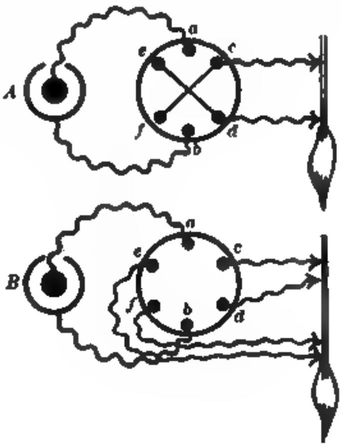


FIG. 13.—Method of recording muscular contraction.

The simplest method of recording the extent of the muscular contraction is to connect the muscle by means of a fine thread with a light lever, and let the point of the lever rest against a smooth surface covered with soot, so that when the muscle contracts it shall draw up the lever and trace a line of corresponding length upon the blackened surface. The combination of instru-

rius muscle, which is clamped in the middle firmly enough to prevent the contractions of one half from moving the other, but not enough to interfere with the conduction-power of the tissue. The record of the contractions is best obtained by the double myograph of Hering (Fig. 15), which permits the recording levers attached to the two ends of the muscle to write directly under each other, so that any difference in the beginning of the contraction of the two halves of the muscle is immediately recognizable from the relative positions of the records of their contractions.

The current is applied to the two extremities of the muscle by non-polarizable electrodes. In all experiments with the direct battery current it is essential to employ non-polarizable electrodes. The form devised by Hering is very useful where the current has to be applied directly to the muscle, because the two electrodes are hung from pivots in such a way that they move with the movements of the muscle, and hence do not shift their position when the muscle contracts. Some kind of apparatus has to be employed for quickly reversing the direction of the current. A convenient instrument for this purpose is Pohl's mercury commutator (Fig. 16). This instrument consists of a block of insulating material in which are six little cups containing mercury, which is in connection with binding-posts on the sides of the block. Two of the mercury cups on the opposite



FIGS. 16, 17.—Pohl's mercury commutator.

sides of the block a and b (Fig. 17, A), are connected by wires with the battery; two others, c and d, are connected with wires which pass to the electrodes; the remaining two on the opposite side of the block, e and f, are joined by movable good conducting wires with the cups c and d in such a way that c connects with f, and d with e. Two anchor-like pieces of metal are connected by an insulated handle, and are so placed that the stocks of the anchors dip into the mercury cups a and b (Fig. 16). The anchors can be rocked to one side or the other, so that the ends of the curved arms shall dip into the cups c and d (in which case cup a will be connected with cup c, and cup b with cup d), or so that the other ends of the arms shall dip into cups e and f (in which case cup a will be connected with cup e, and by means of the cross wire with cup d, and cup b will be connected with cup f, and by means of the cross wire with cup c). By the arrangement shown in Fig 17, A the current can pass from the battery by way of a and c down the nerve, and by way of d and b back to the battery: or it can pass from the battery by way of a, e, d, and in the reverse direction, up the nerve and back to the battery, by way of c, f, b. There are many other forms of apparatus, generally known as pole-changers, which may be employed to reverse the current.

The commutator can be used in another way (see Fig. 17, B). If the battery be connected with it as before, and the cross wires be removed, the current can be sent at will into either one of two separate circuits. For instance, if the cups c, d be connected with

experiments that the tetanus which results from closing a strong current remains located at the kathode, and the tetanus following the opening of the current remains located at the anode.

The same is true of the nerve as of the muscle; the irritating process which is called out by the sudden entrance of a battery current into a nerve starts from the negative pole, the kathode, and spreads thence throughout the nerve, while the irritating process excited by the cessation of the flow of the current starts from the region of the positive pole, the anode, and spreads from that point throughout the nerve. A proof of this was obtained by Von Bezold, who observed the difference in the time between the moment of excitation and the beginning of the contraction of the muscle, when the nerve was excited by opening and by closing the current, with the anode next to the muscle, and with the kathode next to the muscle. He found the time to be longer when the current was closed if the kathode was the more distant, and to be longer when the current was opened if the anode was farther from the muscle. Evidently in the case of the nerve as of the muscle, the irritable substance subjected to the current is not all affected alike. The current does not set free the irritating process at every part of the nerve, but produces peculiar and different effects at the two poles, the change which occurs at the kathode when the current is closed being of a nature to cause the development of the excitatory process which awakens the closing contraction, and the change which occurs at the anode when the current is opened being such as to cause the development of the excitatory process which calls out the opening contraction.

Closing contractions are stronger than opening contractions. The irritation developed at the kathode is stronger than that developed at the anode. It is true of both striated and unstriated muscles that an efficient irritation can be developed at the kathode with a weaker irritant than at the anode. Moreover, a greater strength of current is required to produce opening than closing continued contractions.

The same may be said of nerves. If one applies a very weak battery current to the nerve of a nerve-muscle preparation, he notices when he closes the key a single slight contraction of the muscle, and when he opens the key, no effect. If he then increases the strength of the current very gradually, and tests the effects of the making and breaking of the current from time to time, he observes that each time the strength of the current is increased the closing contraction, which is due to irritation originating in the part of the nerve subject to the kathode, grows stronger, and finally contractions are also seen when the circuit is broken, the irritation process developed at the anode having become strong enough to excite the muscle. These opening contractions at first are weak, but gradually increase in strength, until with a medium strength of current vigorous contractions are seen to follow both opening and closing of the current. If the strength of the current be still further increased, it is found that either the closing or opening contraction begins to decrease in size, and if a very strong current be employed, the closing or opening con-

the current may excite other parts than those which it is intended to excite and false conclusions may be reached.

In case currents of high potential are employed, another source of error may arise through electrostatic charging of distant parts.

Spread of Electrostatic Charges.—If the primary coil of an induction apparatus be connected with a battery by the closure of a key in the primary circuit, the sudden flow of current through the coil is accompanied by a transient change in the stress of the magnetic field about the coil. This change in the magnetic field induces an alteration in the electrical condition of the wire of the secondary coil of the apparatus, and the terminals of this coil undergo a rapid change of electrical potential, the one becoming positive, the other negative. If two electrodes be connected with the binding posts of the secondary coil, they become the terminals of the coil and are given, one a positive, the other a negative charge. The same thing happens when the key in the primary circuit is opened. In both cases the change of potential is only momentary in its duration. The effect of opening the primary circuit is considerably stronger than that of closing the circuit, for reasons stated on page 33.

If the two electrodes are connected by a conducting material, an electric current will flow from one to the other at the instant the change of potential takes place. If the electrodes be connected by the nerve of a nerve-muscle preparation, an electrical current will flow through the nerve; the nerve will be excited, a nerve-impulse will be developed and be transmitted along the nerve to the muscle and cause it to contract. It not infrequently happens, if the current entering the primary coil is strong and a large electromotive force is developed in the secondary coil, that the exciting effect of the sudden electrical change is not confined to the part of the nerve directly connecting the electrodes, but spreads to distant parts of the nerve, and even to the muscle. This is shown by the fact that the muscle will contract even after a moist ligature, tied tightly about the nerve, has broken the continuity of its protoplasm and so prevented the nerve impulse from reaching the muscle. In such a case the contraction of the muscle is due to an irritation of the nerve beyond the point to which the ligature was applied or to the direct excitation of the muscle itself.[1]

If it is found that the muscle will contract after the nerve has been crushed by the ligature, it will also be found that it will contract in case one electrode be removed from the nerve, so that it remains connected with only one pole of the induction apparatus. To understand this, we must look upon the muscle as the terminal of the pole of the secondary coil with which it is in connection. When the potential of the poles of the secondary coils is suddenly changed, the change of potential spreads through all conducting bodies connected with these poles, and in the case in question it passes, by way of the wire, electrode, and nerve, to the muscle. In short, the muscle, like any conductor, is charged up, and in the process of charging there is a flow of current which excites the nerve and muscle.

[1] Du Bois-Reymond: *Untersuchungen über thierische Electricität*, Bd. i. S. 423.

to a dense flow of current, will be excited and the muscle will contract. Unless the primary current is very strong the electromotive force developed in the secondary coil on the closing of the primary circuit may be too weak to cause contraction, and only the effect of opening the circuit may be observed; in any case, the effect of breaking the primary circuit will be the stronger. More striking results will be obtained if the primary current be rapidly made and broken by an automatic interrupter introduced into the primary circuit; the muscle will then be excited by a series of rapidly following shocks.

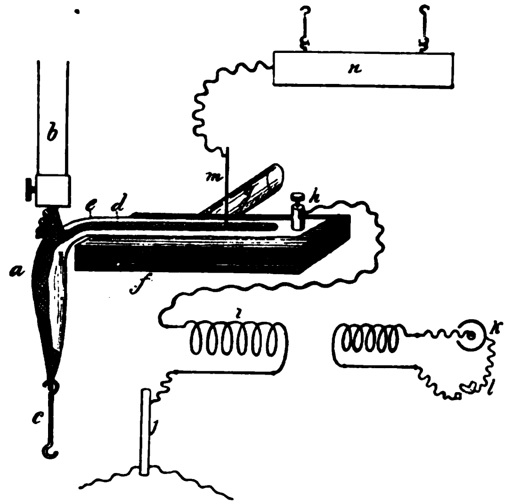


FIG. 22.—Unipolar, localized excitation of nerve. By this arrangement a large part of the surface of the nerve and muscle is brought into immediate connection with the secondary coil through the sheet of gold-foil. The nerve is locally excited at the point that is touched by the needle, because the current going to charge the tin-foil conductor passes out of the nerve at this point as a dense stream. The muscle (a) is supported by an insulating clamp of lead-glass and vulcanite (b), and is connected to the writing lever by a dry lead-glass hook (c); the nerve (d) lies on a sheet of gold-foil (e), which is also wrapped about the muscle, and which rests on a block of vulcanite (f) supported by a glass rod (g); the gold-foil is in close contact with the binding-post (h), and this is connected with one terminal of the secondary coil (i) of an induction apparatus, the other terminal being connected with a gas pipe (j), and so with the earth: in the primary induction circuit there are a battery (k) and a key (l); the needle (m) is connected with a large conductor (n), which is composed of a board covered with tin-foil, and is suspended from glass hooks.

For the sake of simplicity we have thus far only spoken of the charging of the preparation from the secondary coil. It must be borne in mind, however, that the change in the electrical condition of the secondary coil lasts only an instant, and the terminals of the coil and the tissues connected with them immediately return to their original potential, this change being accompanied by a backward surge of the electrical wave from the muscle through the nerve, electrodes, and wire to the coil, and this reverse current acts like the charging current to cause excitation. The charging and discharging processes follow each other with such rapidity, however, that they act upon the tissues as a single excitation.

To Prevent the Spread of Current.—As we have seen when the nerve of a nerve-muscle preparation is connected by two electrodes with the poles of

In a like manner if a nerve-muscle preparation be isolated, as shown in Fig. 22, and a needle, held in the hand or connected with a large metallic conductor or a condenser, be brought in contact with some point of the nerve, the excitation which occurs on the opening and, with a strong current, on the closing of the primary circuit will be strictly limited to the part of the nerve touched by the needle. This method can be used to advantage in studying the rate of conduction in nerves or any problem which requires strict localization of electric excitation.

(*d*) *Effect of the Duration of the Electric Current on its Power to Irritate Nerves and Muscles.*—As we have seen, a constant battery current, when flowing uninterruptedly through a motor nerve, does not ordinarily excite it; very slow variations in the strength of the current also fail to irritate; but rapid alterations in the strength, whether in the direction of increase or decrease, act as vigorous stimuli. For example, medullated nerves are irritated more vigorously by the rapid changes of intensity of induced currents than by the somewhat slower changes occurring at the make and break of battery currents. Within certain limits, at least, the more rapidly the intensity of the current changes, the greater the irritating effect upon nerves. That there is a limit even for the rapidly reacting protoplasm of medullated nerves is shown by the fact that by unipolar excitation the charging and discharging of the condensers through a nerve is the more effective the greater the capacity of the condensers. The process is more prolonged if the condenser is large, and the effect is greater.[1] Not all nerves are equally susceptible to rapid alterations of the intensity of the current. Non-medullated nerves do not appear to react as readily as medullated to electric currents of short duration. For instance, the nerves of the claw muscles of the crab are not readily excited by induced currents, and respond better to the more prolonged influence of the closing and opening of battery currents.[2]

The question now arises, Is the reaction of muscle to electric currents the same as that of nerves? Experiment shows that muscles which have been removed from the action of nerves, by means of curare, differ from medullated nerves in that they are excited more vigorously by the opening and closing of battery currents; less vigorously by making and breaking induction currents. This latter fact is well seen in experiments in which two gastrocnemius muscles from the same frog, one of which has been curarized and the other not, are connected with an induction apparatus in series, so that the current shall flow through them both in the same direction. If the primary current be made and broken, the non-curarized muscle will respond to a weaker induction shock than the curarized. By the curarized muscles the maximal contraction got on opening and closing a battery current is both higher and more prolonged than that to be obtained with a single induction shock. Unstriated muscles exhibit this difference to a still greater degree than striated muscle; they react well to the closing of battery currents of medium

[1] Hermann: *Handbuch der Physiologie*, Bd. ii. Theil 1, S. 88.
[2] Biedermann: *Elektrophysiologie*, 1895, Bd. ii. S. 546.

When human striated muscle undergoes degeneration as a result of an injury to its nerve, the degenerating muscle comes to resemble normal unstriated muscle in its reactions to electricity, responding feebly to induced currents, at a time when irritability to mechanical stimuli and to direct battery currents is even increased. This is used by clinicians as a means of diagnosis of the condition of the nerve and muscle.

From what has been said it is evident that the rule laid down by Du Bois-Reymond (see p. 32) must be modified in so far that there is for each tissue a limit to the rate at which a change of intensity of the electric current acts as an irritant.

(*e*) *Effect of the Angle at which the Current Enters and Leaves the Muscle and Nerve.*—The angle at which the current acts on the muscle-fibre has been found to have a bearing upon its power to stimulate. Leicher[1] succeeded in obtaining definite experimental evidence that when the current is so sent through a muscle as to cross it at right angles to its fibres it has no irritating effect, and that its power to stimulate increases as the angle at which the threads of current strike the muscle-fibres decreases, being greatest when the current passes longitudinally through the fibres.

Similarly, it was found by Albrecht and Meyer[2] that the irritating effect of the electric current is most active when it flows longitudinally through the nerve, and that it is altogether absent when it flows transversely through it. This view is doubted by some observers, who would attribute the difference observed to differences in the electrical resistance. It is true that the resistance to cross transmission is greater than to longitudinal transmission, but it is not likely that this difference suffices to explain the lack of response to currents applied at right angles to the nerve-axis.

Relative Efficacy of the above Conditions upon the Irritating Power of the Electric Current.—When a current is applied to an irritable part of a nerve or muscle at an angle suitable to excitation, the stimulating effect of the current depends upon the rate at which its intensity is changed, the strength and density of the current, *i. e.* its intensity, and the duration of the current.

Fick[3] gives the following schema (Fig. 24) for the different ways in which the intensity of the electric current may be varied, and compares the effects of these different methods of application of the current. It must be remembered that a decrease of intensity acts no less than an increase to produce excitation. In the above schema the abscissa represents the time, and the ordinates the strength, of the current. Suppose the rise of intensity has a form such as is represented in *a*, Figure 24—that is, that the strength of the current increases to a considerable height, but very slowly. Such a rate of change, even though the rise of intensity were continued until the strength of current was very great, would have no exciting effect upon a nerve and might

[1] *Untersuchungen aus dem physiologischen Institut der Universität Halle*, Heft i. S. 5.

[2] *Pflüger's Archiv*, 1880, Bd. xxi. S. 462.

[3] *Beiträge zur vergleichende Physiologie der irritablen Substanzen*, Braunschweig. 1863.

Moreover, by a given rate of change of intensity, the stimulating effect varies with the strength of the current employed. Pflüger in his celebrated monograph, *Untersuchungen über die Physiologie des Elektrotonus*, published in Berlin, 1859, p. 454, formulated the following rule for the result of excitations under varying conditions:

Pflüger's Law of Contraction.

	Ascending Current.		Descending Current.	
	Closing.	Opening.	Closing.	Opening.
Weak current	Contr.	Rest.	Contr.	Rest.
Medium "	Contr.	Contr.	Contr.	Contr.
Strong "	Rest.	Contr.	Contr.	Rest.

To understand this so-called "law of contraction" we must bear in mind certain fundamental facts, namely:

a. When a nerve is subjected to a battery current, an excitatory process is developed in the part of the nerve near the kathode when the current is closed, and in the part of the nerve near the anode when the current is opened (see p. 38).

b. The excitatory process developed at the kathode is stronger than that developed at the anode (see p. 38).

c. A third fact which is of no less importance, and which will be considered in detail when we study the effects of the constant current on the irritability and conductivity of nerve and muscle (see p. 95), is the following: During the time that a strong constant current is flowing through a nerve, the conducting power is somewhat lessened in the part to which the kathode is applied, and is greatly decreased, or altogether lost, in the region of the anode; moreover, at the instant that the current is withdrawn from the nerve the conducting power is suddenly restored in the region of the anode, and greatly lessened, or lost, in the region of the kathode.

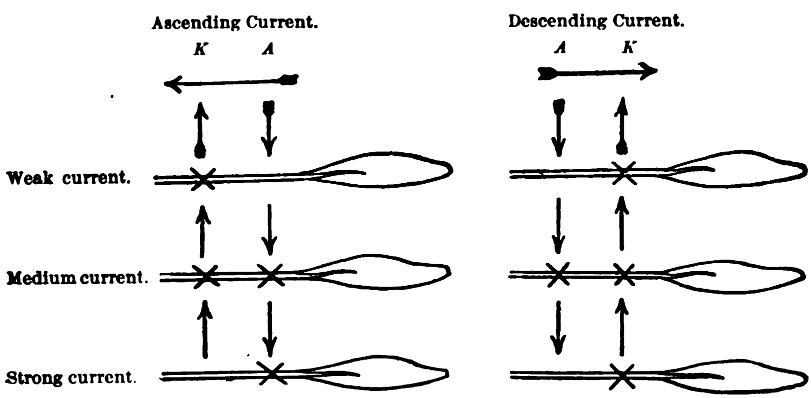


FIG. 25.—Diagram illustrating Pflüger's law.

The twelve cases included in the above table can be represented in the following diagram (Fig. 25), in which a cross is marked at the part of the nerve

The density of the current entering any structure beneath the skin will depend in part upon the size of the electrode directly over it—that is, the amount to which the current is concentrated at its point of entrance or exit—in part on the nearness of the structure to the skin, and in part on the conductivity of the tissues of the organ in question as compared with the tissues and fluids about it. If the conditions be such as are given in Figure 27, the current will not, as in the case of the isolated nerve, enter the nerve at a given point, flow longitudinally through it, and then leave it at a given point; most of the threads of current will pass at varying angles diagonally through the part of the nerve beneath the positive pole, then flow through the fluids and tissues about the nerve, until, at a point beneath the negative pole, the concentrating threads of current again pass through the nerve. A distinction is to be drawn between the physical and physiological anode and kathode. The physical anode is the extremity of the positive electrode, and the physical kathode is the extremity of the negative electrode; the physiological anode is the point at which the current enters the tissue under consideration, and the physiological kathode is the point where it leaves it. There is a physiological anode at every point where the current enters the nerve, and a physiological kathode at every point where it leaves the nerve; therefore there is a physiological anode and kathode, or groups of anodes and kathodes, for the part of the nerve beneath the positive electrode, and another physiological anode and kathode, or collection of anodes and kathodes, for the part of the nerve beneath the negative electrode.

Fig. 27.—Rough schema of active threads of current by the ordinary application of electrodes to the skin over a nerve (ulnar nerve in the upper arm). The inactive threads are given in dotted lines (after Erb: *Ziemssen's Pathologie und Therapie*, Bd. iii. S. 76).

To understand the effect upon the normal human nerve of opening and closing the battery current, it is necessary to bear in mind three facts, viz.:

1. At the moment that a battery current is closed, an irritating process is developed at the physiological kathode, and when it is opened, at the physiological anode.

2. The irritating process developed at the kathode on the closing of the current is stronger than that developed at the anode on the opening of the current.

3. The effect of the current is greatest where its density is greatest.

The amount of the irritation process developed in a motor nerve is estimated from the amount of the contraction of the muscle. The contraction

beneath the physical anode, than in the region of the physiological anode, beneath the physical kathode.

These differences in the strength of the irritation process developed in these different regions is well shown by examining the reaction of nerves to currents of gradually increasing strength. The effect of the opening and closing irritation is seen to be as follows:

Weak currents.	Medium currents.	Strong currents.
KCC	KCC	KCC
——	ACC	ACC
——	AOC	AOC
——	——	KOC

The natural order, therefore, would be KCC, ACC, AOC, KOC. Sometimes, however, AOC is stronger than ACC; this happens when on account of the relation of the surrounding tissues to the nerve the density of the current at the physiological anode is great as compared with the density at the physiological kathode. Bordier[1] tested the strength of battery current necessary to awaken minimal sensations by unipolar excitations, and found the effect to be greatest by KC, then AC, then AO; and that it was least by KO—*i. e.*, sensory behave like motor nerves.

In testing the effect of the battery current on the nerves and muscles of man, it is customary to use one small and one large electrode (Fig. 6, *d*, *e*, *f*). The small electrode is placed over the part to be stimulated, while the large electrode is put over some distant portion of the body. This arrangement causes the current to be condensed, and hence efficient, when it enters or leaves the small exciting electrode, and to be diffused, and hence ineffective, at the large indifferent electrode. For example, the indifferent electrode may be placed on the sternum or over the back of the neck, while the exciting electrode may be put over the ulnar nerve at the elbow. The two poles may be connected with the battery, a pole-changer, rheostat, milliampèremeter, and exciting-key being introduced in the circuit. The pole-changer permits the exciting pole to be made A or K at the wish of the operator, the rheostat allows the strength of current to be raised gradually, and the milliampèremeter shows the strength of the current employed. With this arrangement the reaction of the nerve can be readily tested.

When the currents employed are strong, it occasionally happens in the case of men that not only are the make and break followed by the usual rapid contractions of short duration, but during the closure of the current there is a continued contraction—galvanotonous, as it is sometimes called. This is especially seen under certain pathological conditions.

When the nerve or muscle is diseased we may have the above order changed, and ACC obtained with weaker currents than KCC, and KOC than AOC (Babinski)[2]. This is known as the reaction of degeneration. Under

[1] Bordier: *Archives de Physiologie normale et Pathologique*, 1897, pp 543–553.

[2] Babinski: *Comptes rendus de la Société de Biologie*, 1899, p. 343.

of the nerve. A nerve can be irritated thirty to forty times, at intervals of three to four minutes, by blows from a weight of 0.485 gram, falling 1 to 20 millimeters, the contractions of the muscle, weighted with 30 to 50 grams, varying from minimal to from 3 to 4 millimeters in height. Rapidly following light blows or twitches applied to a motor nerve, by the tetanomotor of Heidenhain or Tigerstedt, excite a series of contractions in the corresponding muscles which fuse more or less into a form of continuous contraction, known as tetanus.

Not only may a nerve be excited by bringing sudden pressure to bear on it, but the sudden removal of weights or a sudden lessening of tension irritates.[1] Kühne long ago called attention to the excitation of sensory fibres of the ulnar nerve of man on the removal of pressure. The cause is probably the irregular return of the semi-fluid parts of the nerve to their normal relations.

Mechanical applications to nerve and muscle first increase and later lessen and destroy the irritability. Thus pressure gradually applied first increases and later reduces the power to respond to irritants. Stretching a nerve acts in a similar way, for this also is a form of pressure; as Valentin said, the stretching causes the outer sheath of the nerve to compress the myelin, and this in turn to compress the axis-cylinder. Tigerstedt states:[2] "From a tension of 0 up to 20 grams the irritability of the nerve is continually increased, but it lessens as soon as the weight is further increased."

Surgically the stretching of nerves is sometimes employed to destroy their excitability. Slight stretching heightens the excitability and even quite vigorous stretching has only a temporary depressing effect unless it be carried to the point of doing positive injury to the axis-cylinder, and of causing degeneration. As nerves have the power to regenerate, they may recover from even such an injury.

The irritability of muscles is likewise increased by moderate stretching and destroyed if it be excessive. Thus slight stretching produced by a weight causes a muscle to respond more vigorously to irritants. Similarly tension of the muscles of the leg, produced by slight over-flexion or extension, makes them more irritable to reflex stimuli, as in the case of the knee-jerk and ankle-clonus. Tension must be very marked to permanently alter the irritability of the muscles.

Effect of Temperature.—Changes in temperature, if sudden and extreme, irritate nerves and muscles. If the nerve or muscle be quickly frozen or plunged into a hot fluid it will be excited and the muscle be seen to contract. The cause of the irritation has been attributed to mechanical or chemical alterations produced by the change of temperature. The ulnar nerve at the elbow is excited if the part be dipped into ice-water and allowed to remain there until the cold has had time to penetrate; as is proved by the fact that in addition to the sensations from the skin, pain is felt which is attributed by the subject of the experiment to the region supplied by the nerve. As the effect

[1] v. Uxhull: *Zeitschrift für Biologie*, 1894, Bd. xxxi. S. 148; 1895, Bd. xxxii. S. 438.
[2] *Op. cit.*, S. 43.

slows chemical processes and increases the endurance. It is noticeable that nerves and muscles remain irritable much longer than ordinarily in case the body be cooled before their removal. In the case of a mammal, the irritability may last from six to eight hours instead of two and a half, while in the case of frogs it may be preserved at 0° for ten days, although at summer heat it lasts only twenty-four hours. In the case of frogs which have been kept at a low temperature the irritability becomes abnormally high when they are warmed to ordinary room-temperature.

Effect of Chemicals and Drugs.—The irritability of nerve and muscle protoplasm is markedly influenced by even slight changes in its constitution. If a nerve or muscle be allowed to lie in a liquid of a different composition from its own fluid, and especially if such a liquid be injected into its blood-vessels, an interchange of materials takes place which results in an alteration of the constitution of the tissue and a change in its irritability. Indeed, the only solutions which fail to alter the irritability are those which closely resemble serum and lymph. Fluids having other than the normal percentage of salts have a marked effect, while even the absence of proteids appears to have little influence unless continued for a considerable time.

Pure water acts as a poison to protoplasm, soon destroying its life. Through diffusion and osmosis it is imbibed into the cells at the same time that the salts pass out, and the resulting change in the physical and chemical condition of the tissue cause if rapid, first an increase, and in any case later a decrease, and finally a total loss of irritability. Thus water injected into the blood-vessels of muscles first excites contraction and later destroys the irritability, and results in the condition known as water rigor. These effects are prevented by the presence of small amounts of salt. A sodium chloride solution, of a strength of 6 parts per 1000 of distilled water, has been called the physiological solution, because it was supposed to have no effect on the irritability of nerves and muscles of cold-blooded animals; even this solution, if long continued, gradually increases and later decreases the irritability. A solution containing 7 parts of sodium chloride per 1000 is more nearly isotonic to the fluids of cells of the frog, and one containing 9 parts per 1000 is approximately in osmotic equilibrium with the fluids of the cells of the mammal. Such fluids cannot be properly regarded as physiological solutions, however, for this would mean that they would cause no change in constitution of the cells. They contain only one of the salts essential to the normal activity of the tissues, and the difference in the partial pressure of the other salts of the muscle would cause the muscle cells to lose some of each of these, and, as a result, to have their irritability altered. The importance of the individual salts present in the fluids normally surrounding the tissues, and the need that they should be present in definite proportions, were most strikingly demonstrated by experiments, by Ringer and others, on the nature of the fluid which is essential to the maintenance of the activity of the isolated heart of the frog. These experiments have shown that not only Na, but Ca and K are essential. The heart of the terrapin can be kept

shows irregular contractions, as the different fibres of the nerve are one after the other affected. If the drying has not been continued too long, the normal irritability may be restored by supplying water. Muscles behave like nerves in these respects.

Most drugs and chemicals capable of altering the irritability of nerves and muscles first increase and later destroy the irritability. If the change in the chemical constitution of the nerve is sufficiently rapid, it may be accompanied by the phenomena of excitation. For example, veratria, eserin, digitalis, most mineral acids, and many organic acids, free alkalies, most salts of heavy metals, destroy the irritability of nerves and muscles, as a rule after first producing increased excitability. Potash salts, if concentrated, rapidly kill, but excite less than soda compounds. Verworn says: Acids, alkalies, and salts have a similar effect on the protoplasm of a thick pseudopod of one of the rhizopods of the Red Sea; they first excite and later paralyze, acting like narcotics on the central nervous system.

Ammonia, carbon disulphide, and ethereal oils may destroy the irritability of nerves without causing excitations, at least not in sufficient amount to produce visible muscular contractions. If applied directly to the muscle, however, these substances excite contractions.

The attempt to ascertain some exact relation between the molecular weight of different salts and acids and their destructive power has encountered too many exceptions for the establishment of any definite rule; in general, however, the higher the molecular weight the stronger the effect on the muscle.[1] Many gases and vapors have a marked effect on the irritability and activity of protoplasm.[2] Carbonic-acid gas, tobacco-smoke, the fumes of ether, alcohol, and chloroform, applied directly to exposed nerves, first stimulate, later anæsthetize, and finally kill. CO_2 has a very powerful effect, even a fiftieth of a milligram sufficing to influence profoundly the activity of the protoplasm of the nerve, a fact of considerable importance if we recall that this gas is produced by the normal oxidation of carbon within the tissues of the body. Tobacco-smoke acts like CO_2 and probably because of the CO_2 which it contains. Alcohol first excites and then paralyzes the nerve. If the fumes of alcohol have not acted for too long a time, the paralyzed nerve may recover its function, and the same is true for ether and chloroform. These vapors, if present in considerable quantities act rapidly upon exposed nerves; thus ether (diethyl oxide) will anæsthetize a nerve in three minutes; if the drug be then removed, the nerve can completely recover in five minutes. Chloroform would appear to be a more dangerous anæsthetic than ether, as recovery of the nerve is less likely to occur in case the anæsthetic action is somewhat prolonged. Many other gases and fumes chemically irritate and kill nerve-muscle protoplasm.

From all these results it becomes evident that the normal irritability of

[1] Blumenthal: *Pflüger's Archiv*, 1896, Bd. 62, S. 513.

[2] Waller: *Lectures on Physiology*, first series, "On Animal Electricity," London, 1897, pp. 42–46.

out, and make a little vesicle at the region of the anode. A similar inhibitory influence may be observed upon an ordinary striated muscle at the point of application of the anode, if it be in a condition of tonic contraction when the battery current is sent into it. During the flow of the constant current through a muscle, the irritability is increased in the region of the kathode and decreased in the region of the anode. When the current is withdrawn from the muscle, on the other hand, the irritability of the kathode is found to be decreased, and at the anode to be increased.

Effect of the Electric Current upon Nerves.—The polarizing effects of a continuous constant current are the same upon a nerve as upon a muscle, with the exception that in the case of the nerve the condition of altered irritability is not so strictly limited to the point of application of the anode and kathode, but spreads thence throughout the part of the nerve between the two electrodes, the intrapolar region, as it is called, and for a considerable distance into the parts of the nerve through which the current does not flow, *i. e.* the extrapolar region. The term electrotonus has been applied to the effects of battery currents on nerves and muscles, and includes two sets of changes—(1) manifested by the alterations of irritability which we are considering; (2) exhibited in changes of the electrical condition of the tissue.

There can be little doubt that both of these sets of changes are the result of electrolytic alterations of the nerve protoplasm, caused by the flow of the polarizing current. We shall consider here only the former of these sets of changes. The true nature of the electrotonic changes of the electrical condition of the nerve, and their relation to the nerve impulse, embrace a number of difficult problems, which are still under discussion and cannot be profitably considered here.[1]

The most important work on the influence of the constant current on the irritability of nerves was done by Pflüger.[2] He ascertained the electrotonic effects of the polarizing current to be most vigorous in the immediate vicinity of the anode and kathode, and to spread thence in both directions along the nerve. He called the change produced in the nerve in the region of the anode "anelectrotonic," and the condition itself "anelectrotonus;" while the change at the kathode was termed "katelectrotonic," and the condition "katelectrotonus." The same names are given to the effects of battery currents upon muscles.

To test the effect of a constant battery current upon the irritability of a nerve, put the nerve of a nerve-muscle preparation upon two non-polarizable electrodes (*A*, *K*, Fig. 29) which are placed at some little distance apart and at a considerable distance from the muscle. Connect these electrodes with a battery, introducing into the circuit a key (*k*), which permits the current to be quickly thrown into or removed from the nerve, and a commutator (*C*), which allows the current to be reversed and to be sent through the nerve in

[1] Waller: *Lectures on Animal Electricity*, London, 1897; Biedermann: *Electrophysiology*, translated by F. A. Welby, 1898, vol. ii.

[2] Pflüger: *Untersuchungen über die Physiologie des Electrotonus*, Berlin, 1859.

movement, and shocks of medium strength, if given at short intervals, may each cause a larger contraction than its predecessor, until a certain height of contraction has been reached, beyond which there is no further increase possible. We shall consider these so-called "staircase contractions" more carefully later (see page 112). When irritations follow each other very rapidly the whole character of the contraction is changed, and the muscle, instead of making rapid single contractions, enters into the condition of apparently continuous contraction known as tetanus, during which it shortens considerably more than it does when making single contractions. Increase in irritability plays only a comparatively small part in the production of this remarkable phenomenon, which we shall study more carefully when we come to the mechanical problems involved in muscular contractions.

Rapidly repeated stimuli, though at first favorable to activity of a muscle, soon exert an unfavorable influence by causing the lessened irritability which is associated with fatigue.

When a nerve is excited there is a change in its electrical condition, and the extent of the change is generally believed to be an indication of the extent to which the protoplasm of the nerve has become active in response to excitation. Waller,[1] taking the amount of change in the electrical condition of the nerve as an evidence of the ability of the protoplasm to react under varying conditions, found that repeated excitation increases the activity of the nerve as it does of the muscle. Repeated excitation of a nerve at suitable, regular intervals causes a staircase-like increase in the strength of the electrical response, the record resembling that got by staircase contractions of muscles (see page 112). Moreover, if the electrical condition of the nerve is tested by a series of excitations of equal strength before and after it is subjected to a tetanizing current, the strength of the variations is found to be increased.

If a second stimulus follows the first too soon, it may be wholly ineffective; at least this has been found to be the case with certain forms of protoplasm. It has been shown that heart muscle has a "refractory period," as it is called, responding very imperfectly to stimuli applied to it just before and during its systole.[2] Apparently much the same is true of the nerve. Boycott,[3] using contraction of muscle as a test, and Gotch and Burch,[4] using the current of action as a test, have lately discovered that for a brief period after the nerve has been stimulated it is incapable of responding to a second stimulus. The length of the period of lessened excitability is greatly influenced by temperature; at 4° C., with maximal stimuli, the "critical period" may be 0.007–0.008 second; at higher temperatures it is shorter.

(*b*) *Influences which favor the maintenance of the Normal Physiological Condition of Nerve and Muscle.—Effect of Blood-supply on Nerve and Muscle.* —The vascular system is a path of communication between the several organs

[1] Waller: *Lectures on Physiology*, first series, 1897, p. 68.
[2] Cushing: *Journal of Physiology*, 1897, vol. xxi. p. 214.
[3] Boycott: *Ibid.*, 1899, vol. xxiv. p. 144.
[4] Gotch and Burch: *Ibid.*, p. 410.

for mechanical irritants and for direct battery currents (see p. 54) beginning to increase, but the power to respond to electric currents of short duration, as induction shocks, continuing to lessen; indeed, the reactions of the muscle appear to take on more of the character of those of smooth muscle-fibres. The condition of increasing irritability to direct battery currents and mechanical irritants reaches its maximum by the end of the seventh week, and from that time on the power to respond to all forms of stimuli lessens, the excitability being wholly lost by the end of the seventh or eighth month. During the stage of increased excitability fibrillary contractions are often observed.

As in the case of a nerve, so of the muscle the loss of irritability is due to degenerative changes which gradually lead to the destruction of the muscle protoplasm. The cause of the change in the muscle is still a matter of doubt, some regarding it as due to the absence of some nutritive, trophic influence from the central nervous system, others consider it to be the result of circulatory disturbances, consequent upon the lack of a proper regulation of the blood-supply, due to the division of the vaso-motor nerves, and still others attribute it to a lack of exercise, it being no longer stimulated to action. As regards the second view, it may be said that muscles whose vaso-motor nerves are intact, the vessels being innervated through other nerves than those which supply the muscle-tissue proper, as is the case with some of the facial muscles, undergo similar changes in irritability when their motor nerves are cut. As regards the first and last views, it may be said that if the muscles be artificially excited, as by electric stimuli, and thus are exercised daily, the coming on of degeneration can be at least greatly delayed. The question as to whether the anabolic processes within the muscle-cell are dependent on the central nervous system, in the sense of their being specific trophic influences sent from the nerve-cells to the muscles, is still under discussion and need not be considered further in this place. Without doubt the reflex tonus impulses which during waking hours are all the time coming to the muscles are productive of katabolic changes and, indirectly at least, favor anabolism.

(c) *Effect of Influences which result from the Functional Activity of Nerves and Muscles.—Fatigue of Muscles.*—The condition of muscular fatigue is characterized by lessened irritability, decrease in the rate and vigor with which the muscle contracts and liberates energy, and a still greater decrease in the rate with which it relaxes and recovers its normal form. In a sense, whatever induces such a state can be said to cause fatigue, but it is perhaps best to restrict the term to the form of fatigue which is produced by excessive functional activity. The cause of exhaustion which results from overwork is in part the same as the cause of the loss of irritability and power which follows the cutting off of the blood-supply. The working cell liberates energy at the expense of its store of nutriment and oxygen, and through oxidation processes forms waste products which are poisonous to its protoplasm. The fatigue which results from functional activity has, therefore, a twofold

bringing of nutriment and oxygen and the removal of waste matters under ordinary conditions.

Considerable difference of opinion exists as to which of three classes of food-stuffs—proteids, carbohydrates, and fats—supply the energy used by the muscle in ordinary and excessive work, and how these are employed by the muscle.

The question has been studied by examining the character and quantity of waste products liberated from the body during and after excessive muscular work, as compared with those given off when the subject is at rest. Another method has been to test the strength of the muscle in ergographic experiments, and to find the effect of different kinds of food upon the time required for its recovery. Experiments of Fick and Wislicenus,[1] Voit and Pettenkofer,[2] Voit,[3] and others caused the view to become generally accepted that the energy of the muscle by violent muscular work comes largely from the non-proteid substances in the muscles. Later Pflüger and his pupils have gone to the other extreme and conclude that proteid is the chief source of energy.[4]

Very many others have written on both sides of the subject and still a final conclusion has not been reached.[5]

Probably the sugars, and possibly after these the fats are employed by the muscle as the most available form of energy, while the proteid forms a more permanent part of the muscular machine, and is only made use of when the work is exhaustive (see page 166). The taking of any one of these classes of food hastens the recovery from fatigue, and the sooner the more readily it is digested and assimilated (see Metabolism—effect of muscular work).

Normally the muscles are never completely fatigued. It would seem that as the muscles tire and their irritability is lessened, the central nerve-cells which send the stimulating impulses to them have to work harder, and that the nerve-cells give out sooner than the muscles. On the other hand, certain experiments seem to show that the nerve-cells recover from fatigue more rapidly than the muscles do, so that it is an advantage to the organism that they should cease to excite the muscles before muscular fatigue is complete. With the decreasing irritability of the muscle, a feeling of discomfort in the muscle and an increasing sense of effort are experienced by the individual, both of which tend to cause a cessation of contraction, and prevent a harmful amount of work. That such an arrangement would be of service was apparent in the experiments of Maggiora, in which he found that if muscles are forced to work after fatigue has developed, the time of recovery is prolonged out of all proportion to the extra work accomplished.

At the close of even exhaustive muscular work there is always a large amount of energy-holding materials in the blood and tissues, and the rapid,

[1] *Vierteljahresschrift der naturforsche Gesellschaft in Zurich*, 1865, Bd. x. S. 317.
[2] *Zeitschrift für Biologie*, 1866, Bd. ii. [3] *Ibid.*, 1876, Bd. vi. S. 305.
[4] *Pflüger's Archiv*, 1899, Bd. 77, S. 425.
[5] Schafer's *Text-book of Physiology*, 1898, vol. i. p. 912.

mechanical excitation of one part of it might lead to a contraction of the whole. Similarly, a partly dried-up frog may be seen, if mechanically excited, to make movements simulating life. The cause of these movements, also, is not understood. Drying of the muscle in its early stages greatly increases its irritability because of the concentration of the salts, but that does not account for the loss of insulation.

Transmission of Excitation by Means of End-organs.—In spite of the rapid advances which have been made in the histology and physiology of the nervous system during the past few years, we are still in doubt as to the exact way that the axone, the exciting branch of the neurone, stimulates the cell to which it is distributed. In many cases, at least, the axone terminates in an end-organ which is physiologically different from the rest of the cell, and this end-organ is the exciting agent. The relation of the protoplasm of the end-organ to the protoplasm of the cell which it stimulates, whether one of continuity or contiguity, is not certain, but most histological and physiological observations are distinctly in favor of the latter view.

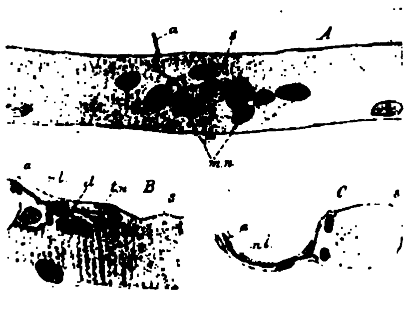


FIG. 31.—Nerve-termination in voluntary muscle of the rabbit, stained in methylen-blue (*intra vitam*), fixed, sectioned, and counter-stained in alum carmin. *A*, surface view; *B*, longitudinal section through nerve-termination and muscle-fibre, *C*, cross-section: *S*, sarcolemma; *n. l.*, neurilemma. (From *Text-book of Histology*, Bohm and Davidoff, revised by G. C. Huber. W. B. Saunders, Philadelphia, 1900).

The physiology of the end-organs of motor axones distributed to striated muscles is best known.

Fig. 31 shows a surface view and a longitudinal and cross-section of the end-organ of an axone supplying a voluntary muscle of a rabbit. The axis-cylinder loses its medullary sheath shortly before reaching the fibre, and the neurilemma becomes continuous with the sarcolemma, so that the axis-cylinder on penetrating the sarcolemma comes into direct contact with the sarcoplasma of the muscle. The sarcoplasma is heaped together at this place, making a little mound, and the axis-cylinder, after dividing into a number of fine terminal twigs, ends in the midst of this mass of sarcoplasma. Evidently the nerve and muscle protoplasm come into very close relation. On the other hand, nerve and muscle protoplasm retain each its peculiar reaction to staining-fluids, and as far as these chemical reactions can show each maintains its peculiar chemical and histological structure. Moreover, the results of physiological experimentation have shown that, although no definite histological boundary has been found between the axone and its terminal organ, the exciting organ must be considered to be a specially differentiated structure, differing widely from the rest of the neurone.

The motor end-organ uses up more time in the excitation of the muscle than would be required for transmission of the excitation through a like amount of nerve- or muscle-substance. It is found by experiment that a

excited in two succeeding experiments at two points, at a known distance apart, and the difference in the time records obtained was the time required for the transmission of the nerve-impulse through this distance.

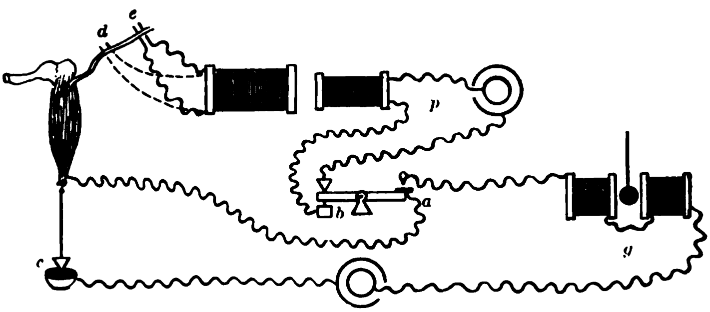


FIG. 35.—Method of estimating rate of conduction in motor nerve of frog, as used by Helmholtz. The horizontal bar *a-b* is supported on an axis in such a manner that when the contact is made at *a* it is broken at *b*, therefore at the same instant a current is made in the galvanometer circuit *g* and opened in the primary circuit of the induction apparatus *p*. When the muscle contracts, the galvanometer circuit is broken at *c*. The nerve was stimulated in two successive experiments at *d* and *e*.

Later, Helmholtz devised a method by which a muscle would record its contractions on a rapidly moving surface, and employed this to measure the rate of conduction in motor nerves. He stimulated the nerve as near as possible to the muscle and let the contraction be recorded; then he stimulated the nerve as far as possible from the muscle, and again had the contraction recorded. The difference in time between the moment of excitation and the beginning of the contraction in the two experiments was due to the difference in the distance that the nerve-impulse had to pass in the two cases, and, this distance being known, the rate of conduction could be readily calculated. By this means he found the rate of transmission in the motor nerves of the frog to be 27 meters per second. In similar experiments upon men he recorded the contractions of the muscles of the ball of the thumb, and noted the difference in the time of the beginning of the contractions when the median nerve was excited through the skin at two different places. He found the average normal rate for man to be about 34 meters per second, a rate which is considerably quicker than that of our fastest express trains, but a million times less than the rate at which an electric current is transmitted along a wire. These determinations are still accepted as approximately correct for human nerves, although they are found to vary very considerably under different conditions, a high temperature and strong irritation quickening the rate to 90 or more meters per second, while cooling may gradually slow the rate and finally stop conduction. Moreover, considerable differences exist in nerves controlling different functions, even in the same animal. Thus Chauveau gives the rate for the fibres of the vagus nerve, which supply the rapidly contracting striated muscles of the larynx, as 66.7 meters per second; and the rate for vagus fibres, controlling the slower smooth muscles of the œsophagus, as 8.2 meters per second. The rate of transmission in the non-medullated nerves of invertebrates appears to be still

FIG. 91.—To show the nuclei of origin and of termination of the third to the twelfth cranial nerves, inclusive, in man. In the nuclei of origin (motor nuclei) the axones are drawn as arising from the bodies of nerve-cells. In the nuclei of termination the relation which exists is typified by the splitting of the axone into a terminal brush. Aside from the nuclei of the cranial nerves, there are represented only the nuclei of origin and termination for the first cervical nerves: Radix anterior cervicalis I., and Radix posterior cervicalis I., and the Funiculus posterior together with the nuclei of termination for its fibres; Nucleus Goll Burdach. The Latin names of the nerves and other structures are placed over the localities to which they apply. The cranial nerves also bear their numbers in Roman numerals. (From *Icones Neurologicæ*: Strümpell and Jakob.)

FIG. 92.—Diagrammatic representation of the lower portion of the human bulb and spinal cord.

The cord is divided into its four regions: 1, medulla cervicalis; 2, medulla dorsalis; 3, medulla lumbalis; 4, medulla sacralis. Within each region the spinal segments bear Roman numbers. On the left side of the diagram the locality supplied by the sensory (afferent) neurones is indicated by one or more words, and these latter are connected with the bulb or the segments of the cord at the levels at which the nerves enter. The afferent character is indicated by the arrow-tip on the lines of reference.

On the right-hand side the names of muscles or groups of muscles are given, and to them are drawn reference lines which start from the segments of the cord in which the cell-bodies of origin have been located.

Within the cord itself, the designations for several reflex centres are inscribed in the segment where the mechanism is localized. For example, Reflexus scapularis, Centrum cilio-spinale, Reflexus epigastricus, Reflexus abdominalis, Reflexus cremastericus, Reflexus patellaris, Reflexus tendo Achillis, Centrum vesicale, Centrum anale (the last two on the left side of the diagram). (From *Icones Neurologicæ*, Strümpell and Jakob.)

FIG. 93.—Schema of the neurones forming the sympathetic nervous system (Huber: *Journal of Comparative Neurology*, 1897, vol. vii.).

A *solid black line* designates the axone from an efferent neurone, with its cell-body in the ventral horn of the cord, and the terminal brush ending in a striated muscle (*m.n.*).

A *black line crossed by short dashes* designates the axone from an afferent neurone, the cell-body of which is in the spinal ganglion, and the peripheral axone of which terminates in the epidermis or some special sense-organ (*s.n.*).

An *interrupted black line* indicates an axone of similar origin to the one just described, but distributed with the fibres of the sympathetic system (*s.s.f.*). At the periphery it terminates in a free ending (*s.s.f.*(1)) or in a Pacinian corpuscle (*s.s.f.*(2)).

A *blue line* shows a pre-ganglionic fibre (of Langley), the cell-body of the neurone being located in the lateral horn of the cord. The axone leaves the cord by the ventral root (as a fibre of very small calibre), passes in the white ramus (*W.R.*), and terminates by a pericellular basket about the body of a sympathetic neurone (drawn in *red*).

The various places where such an axone may terminate are indicated as follows: *a*, axone passing through the chain-ganglion (*I.C.G.*) to terminate within the next higher chain-ganglion: *b*, axone passing as does (*a*), but terminating in the next lower chain-ganglion (*II.C.G.*); *c*, two axones ending in a ganglion of this same segment (*I.C.G.*); *d*, axone passing through the chain-ganglion of the segment and ending in a prevertebral ganglion (*Pr.v.G.*); *e*, axone passing through both a chain-ganglion and a prevertebral ganglion to end in a peripheral ganglion (*Periph.G.*); *f*, axone which gives off a collateral branch to one ganglion (*I.C.G.*) and passes on to terminate in a more distal ganglion (*Pr.v.G.*). Fibres arranged like (*f*) probably account for some of the reflexes obtained from sympathetic ganglia; *g* and *h*, axones representing fibres which regularly pass to any given ganglion from the ganglia above and below it. The sympathetic neurones are drawn in *red*, and about their cell-bodies terminal baskets of other axones (always in blue) are shown. They enter the mixed nerve by the gray ramus (*G.R.*) *m*, the axones of the sympathetic neurones, terminate: *i*, in the muscular coats of the blood-vessels (vaso-motor endings); *j*, in the muscular coats of the viscera (viscero-motor endings), and in heart-muscle (not specially shown in the figure); *k*, in glands (secretory fibres); *l*, in other sympathetic ganglia (a doubtful form of termination).

The figure further shows two "afferent" sympathetic neurones (Dogiel), in *dotted red*: *o*, arising in a peripheral ganglion (*Periph.G.*) and terminating in the prevertebral ganglion (*Pr.v.G.*): *p*, arising in the chain-ganglion (*I.C.G.*) and passing to the spinal ganglion, to terminate about Dogiel's spinal ganglion-cell of "type two," *q* (represented in *solid black*); *q*, spinal ganglion-cell (Dogiel's "type-two"), the terminals of which form baskets about the bodies of the ordinary spinal ganglion-cells.

the discharging cell for a short period of time more excitable. In the same figure the record shows that if a longer interval—here more than three seconds—be allowed to elapse, then the second stimulus from the skin remains inefficient. A similar relation between the two incoming impulses is also found to hold when the stimulus from the skin is made to precede. The curve *B*, Fig. 94, shows the results when both stimuli are inefficient. In this the stimuli (*b* and *a*) produce no effect when given several seconds apart, but when they occur within a short interval (*b′* and *a′*)—in this case 0.13 of a second a contraction of the muscle follows. These various experiments, taken together, show in a beautiful way that in the cases chosen the two sets of impulses tend to reinforce each other, whether they are efficient or inefficient, and without regard to the order in which they come.

This relation between the discharging cell and those by which it is stimulated can be illustrated in still another way. It was observed by Jendrassik[1] that when a patient was being tested for the height of his knee-kick, a voluntary muscular contraction, or an extra sensory stimulus, occur-

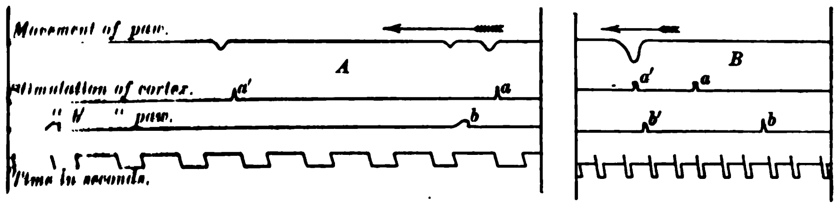


FIG. 94. To show the reinforcing influence of stimuli applied to the cerebral cortex and to the skin of the paw, on the movements of the paw of a rabbit (Exner). The arrows indicate the direction in which the curves are to be read. In curve *A* the cortical stimulus at *a* causes a movement of the paw. Dermal stimulus, within a second, at *b* causes a movement of the paw. Cortical stimulus at *a′* causes a movement of the paw. Dermal stimulus several seconds later at *b′* is ineffective. In curve *B* dermal stimulus at *b* is ineffective. The cortical stimulus at *a* several seconds later is also ineffective. The dermal stimulus at *b′* is ineffective, but if followed within 0.13 second by a cortical stimulus at *a′* a movement of the paw occurs.

ring about the same time that the tendon was struck, had the effect of increasing the height of the kick. This relation was studied in detail by Bowditch and Warren,[2] and they were able with great exactness to measure the interval between the contraction of the muscle used for reinforcement and the time at which the tendon was struck. The curve shown in Fig. 95 represents the results of these experiments. It indicates that, up to 0.4 of a second, the closer together these two stimuli occur the greater the reinforcement. At an interval of 0.4 of a second no effect is produced by the muscular contraction. Increasing the interval only very slightly has, however, the effect of greatly diminishing the height of the knee-kick—*i. e.*, decreasing the strength of the discharge of the efferent cells—and this effect is not lost until the interval is increased to 1.7 seconds, when the voluntary muscular contraction ceases to modify the response. A given efferent cell is thus modified in its discharge according to the several stimuli that act upon it.

[1] *Deutsches Archiv für klinische Medicin*, Bd. xxxiii.

[2] *Journal of Physiology*, 1890, vol. xi.

could be done by voluntarily contracting the flexor muscles of the index finger *before the first failure* to respond to a voluntary stimulus appeared, then

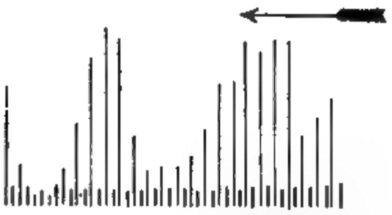


FIG. 120.—A record of the extent of the flexions of the forefinger lifting a weight at regular intervals. The light lines are those for the voluntary contraction; the heavy lines, those for contractions following the direct stimulation of the flexor muscles by electricity. In the former there are periods, in the latter none. The arrow shows the direction in which the record is to be read (Lombard).

the curve expressing this capacity for voluntary work throughout the day was represented as in Fig. 121. Briefly, the curve shows two maxima, at 10 P. M., and 10 A. M., with two minima midway between them. In general

FIG. 121.—Showing at each hour of the day and night how many centimeters a weight of 3000 grams could be raised by repeated voluntary contractions of the forefinger before fatigue sets in. The curve is highest at 10 to 11 A. M., and 10 to 11 P. M.; lowest, 3 to 4 P. M., and 3 to 4 A. M. Circle with dots, observation made just after taking food; square with dot, smoking; *, work done 8 minutes after drinking 15 c.c. of whisky (Lombard).

the immediate effect of taking food is to increase the work done by the subject. Alcohol has the same effect, while smoking produces a decrease.

Further, from day to day this capacity for work is influenced by a number of external conditions—temperature, barometric pressure, etc.

same for all the groups of cells. Hence the cells would, by reason of this fact, have the greatest capability for work in the middle period. Between childhood and old age there is, however, this difference—that while in the former the non-available substances in the cell are developing, not yet having matured, those in the latter have in some way become permanently useless. The degree to which the blood-supply can be controlled varies with age, and the amount of substance capable of yielding energy at various periods of life are different; so that, considering these factors alone, though there are probably others, it may be easily appreciated that the sleep of childhood, maturity, and old age should be quite distinguishable.

Cause of Sleep.—It is recognized that local exercise is capable of producing general fatigue, and the fatigued portions give rise to afferent impulses which, reaching the central system, cause some of the sensations of fatigue; moreover, the active tissues (nerve-cells and muscles) yield as the result of their activity some by-product which is carried by the blood through the central system and becomes the chief cause of sleep. It has been shown by Mosso that if a dog be thoroughly fatigued, giving all the signs of exhaustion, and the blood from this dog be transfused to one that has been at rest, then after the transfusion, the dog which has received the blood from the exhausted animal will exhibit the symptoms of fatigue in full force. The inference is that from the tired animal certain by-products have thus been transferred, and that these are responsible for the reactions. We know, further, that we can distinguish in ourselves different forms of the feeling of fatigue, and that the sensations which follow the prolonged exercise of the muscular system differ from those following the exercise of the higher nerve-centres.

Two things appear as highly probable: First, that there is a wide individual variation in the condition designated as normal sleep. Second, that normal sleep is the result of several sets of influences which need not necessarily be active to the same degree during each period of sleep. Excluding the factor represented by diminution of the external stimuli, sleep has been attributed more or less exclusively to one of the three following influences:

1. *Chemical Influences.*—The theories emphasizing the chemical factor point out that during the normal activity of the body there are formed and taken up by the blood substances which may directly diminish the activity of the nerve-cells and directly or reflexly affect the circulation so as to diminish the supply of blood to the brain, and especially to the cerebral cortex.

2. *Circulatory Influences.*—The vaso-motor theories look upon the changes in the blood-supply as a prime cause of sleep; these changes to be referred in the last instance to the fatigue of the vaso-motor centre in the bulb.

3. *Histological Influences.*—These are made dependent on the shrinkage of nerve-cells during fatigue, the retraction of the dendrites of the cortical cells interrupting the nerve-pathways, or the mechanical separation of the nerve-elements through the intrusion of the neuroglia-cells between them (Cajal). The vaso-motor and chemical theories combined are at present most

energy increasing toward maturity. During middle life the two processes are more nearly in equilibrium, though the total expenditure of energy is probably greatest then; and finally in old age the total expenditure of energy diminishes, while at the same time the anabolic processes become less and less competent to repair the waste. The question why in the nervous system the energies wane with advanced age is but the obverse of the question why they wax during the growing period. The essential nature of these changes is in both instances equally obscure.

Decrease in Weight of the Brain.—Between the fiftieth and sixtieth years of life there is a decrease in the bulk of the encephalon in those persons belonging to the classes from which the greater number of the records have been obtained. So far as can be seen from the present records, there is no marked change in the proportional development of the encephalon in old age, though the loss appears to be slightly greater in the cerebral hemispheres than in the other portions.

Changes in the Encephalon.—The thickness of the cerebral cortex diminishes in harmony with the shrinkage of the entire system. In large measure this must depend on the loss of volume in the various fibre-systems, which, according to the observations of Vulpius, show a senile decrease in the number of fibres composing them. This decrease is more marked in the motor than in the sensory areas. The time at which it commences cannot, however, be accurately stated, owing to the small number of records after the thirty-third year. Where records have been made between this and the seventy-ninth year it appears that there is no decided diminution until after the fiftieth year, though at the seventy-ninth year the decrease is clearly shown. Engel has shown that the branches of the arbor vitæ of the human cerebellum decrease in size and number in old age.[1]

Changes in the Cerebellum.—In the case of a man dying of old age (Hodge) some cells in the cerebellum were found shrunken and others (cells of Purkinje) had completely disappeared. In the antennary ganglion of bees a very striking difference appears between those dying of old age and the adult just emerged from its larval skin. These changes are comparable with those described in mammals, and it further appears that in passing from the youngest to the oldest forms cells have disappeared from the ganglia, and that in the young form of the bee there are some twenty-nine cells present for each one found at a later period.

To the anatomy of the human nervous system in old age contributions have been made by studies on the pathological anatomy of paralysis agitans.[2]

In subjects suffering from this affection the bodies of the nerve-cells are shrunken, pigmented, and show in some cases a granular degeneration; the fibres in part are atrophied and degenerated; the supporting tissues increase, and the walls of the small blood-vessels are thickened. These changes have been found principally in the spinal cord, being most marked in the lumbar

[1] Engel: *Wiener mediciniache Wochenschrift*, 1863.

[2] Ketcher: *Zeitschrift für Heilkunde*, 1892; Redlich: *Jahrbüch für Psychiatrie*, 1893.

region. But the cords of aged persons who do not exhibit the symptoms of paralysis agitans show similar changes, though usually they are not so evident, and hence the pathological anatomy of this disease resolves itself into a somewhat premature and excessive senility of the central system.

Shrinkage, decay, and destruction mark the progress of senescence, and the nervous system as a whole becomes less vigorous in its responses, less capable of repair or extra strain, and less permeable to the nervous impulses that fall upon it; and it thus breaks down, not into the disconnected elements of the fetus, but into groups of elements, so that its capacities are lost in a fragmentary and uneven way.

III. THE SPECIAL SENSES.

A. Vision.

The Physiology of Vision.—The eye is the organ by means of which certain vibrations of the luminiferous ether are enabled to affect our consciousness, producing the sensation which we call "light." Hence the essential part of an organ of vision is a substance or an apparatus which, on the one hand, is of a nature to be stimulated by waves of light, and, on the other, is so connected with a nerve that its activity causes nerve-impulses to be transmitted to the nerve-centres. Any animal in which a portion of the ectoderm is thus differentiated and connected may be said to possess an eye—*i. e.* an organ through which the animal may consciously or unconsciously react to the existence of light around it.[1] But the human eye, as well as that of all the higher animals, not only informs us of the existence of light, but enables us to form correct ideas of the direction from which the light comes and of the form, color, and distance of the luminous body. To accomplish this result the substance sensitive to light must form a part of a complicated piece of apparatus capable of very varied adjustments. The eye is, in other words, an optical instrument, and its description, like that of all optical instruments, includes a consideration of its mechanical adjustments and of its refracting media.

Mechanical Movements.—The first point to be observed in studying the movements of the eye is that they are essentially those of a ball-and-socket joint, the globe of the eye revolving freely in the socket formed by the capsule of Tenon through a horizontal angle of almost 88° and a vertical angle of about 80°. The centre of rotation of the eye (which is not, however, an absolutely fixed point) does not coincide with the centre of the eyeball, but lies a little behind it. It is rather farther forward in hypermetropic than in myopic eyes. The movements of the eye, especially those in a horizontal direction, are supplemented by the movements of the head upon the shoulders. The combined eye and head movements are in most persons sufficiently extensive to enable the individual, without any movement of the body, to receive upon the lateral portion of the retina the image of an object directly behind his back. The rotation of the eye in the socket is of course easiest and most extensive when the eyeball has an approximately spherical shape, as in the normal or emmetropic eye. When the antero-posterior diameter is very much longer than those

[1] In certain of the lower orders of animals no local differentiations seem to have occurred, and the whole surface of the body appears to be obscurely sensitive to light. See Nagel: *Der Lichtsinn augenloser Thiere*, Jena, 1896.

45° with the horizon, since in this position the eye appreciates their real position less accurately than when they are vertical or horizontal. It is diminished, but does not disappear, when the eye, instead of being allowed

FIG. 165.—To illustrate contrast in space-perception (Müller-Lyer).

to wander over the figure, is fixed upon any one point of the field of vision. Hence the motions of the eye must be regarded as a factor in, but not the sole cause of, the illusion.

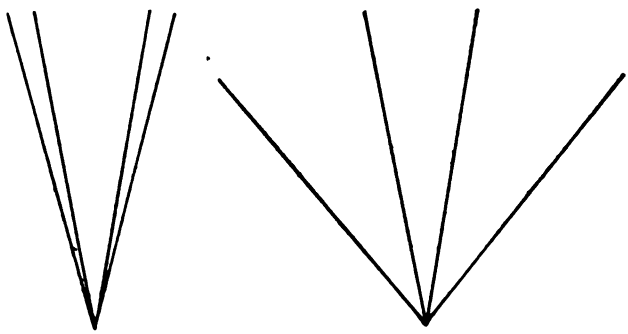


FIG. 166.—To illustrate contrast in space-perception (Müller-Lyer).

The illusion in Fig. 164, where the line *d* is the real and the line *f* the apparent continuation of the line *a*, is to be explained partly by the over-estimation of acute angles and partly, according to Helmholtz, by irradiation.

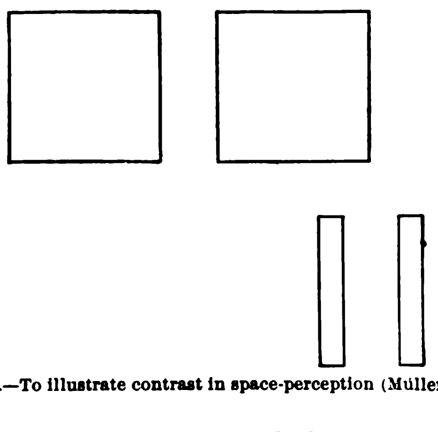


FIG. 167.—To illustrate contrast in space-perception (Müller-Lyer).

The fact that the illusion is greatly diminished by turning the figure on its side seems to show that the tendency to over-estimate vertical dimensions also plays a part in its production.

of a line placed vertically to the plane of the paper does not entirely disappear when one eye is closed. Hence it is evident that there is, as Mrs.

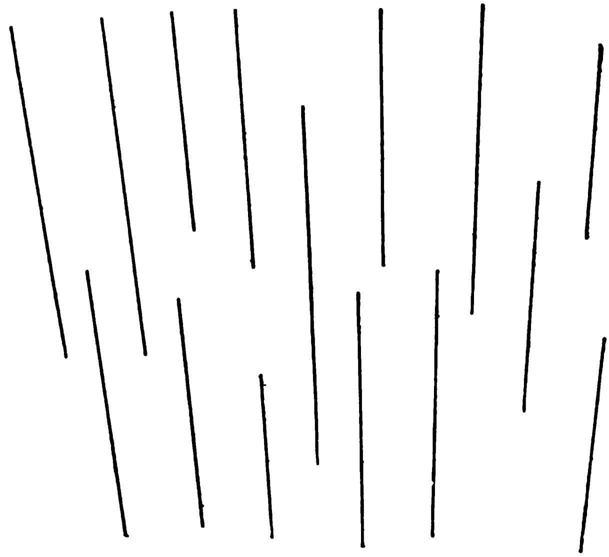


FIG. 177.—Monocular illusion of vertical lines.

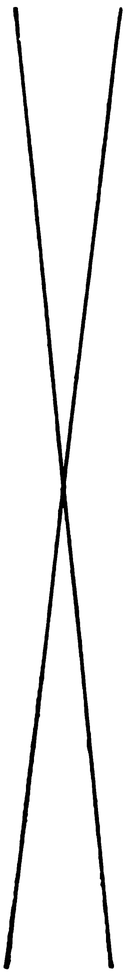


FIG. 176.—Binocular illusion of a vertical line.

C. L. Franklin has pointed out,[1] a strong tendency to regard lines which form their images approximately on the vertical meridian of the eye as themselves vertical. This tendency is well shown when a number of short lines converging toward a point outside of the paper on which they are drawn, as in Figure 177, are looked at with one eye held a short distance above the point of convergence. Even when the lines are not convergent, but parallel, so that their images cannot fall upon the vertical meridian of the eye, the illusion is not entirely lost. It will be found, for instance, that when the Zöllner lines, as given in Figure 163, are looked at obliquely with one eye from one corner of the figure, the short lines which lie nearly in a plane with the visual axis appear to stand vertically to the plane of the paper.

In this connection it may be well to allude to the optical illusion in consequence of which certain portraits seem to follow the beholder with the eyes. This depends upon the fact that the face is painted looking straight out from the canvas —*i. e.* with the pupil in the middle of the eye. The painting being upon a flat surface, it is evident that, from whatever direction the picture is viewed, the pupil will always seem to be in the middle of the eye, and the eye will consequently appear to be directed upon the observer. The phenomenon is still more striking in the case of pictures of which the one represented in Figure 178 may be taken as an example. Here the soldier's rifle

[1] *Am. Journal of Psychology*, vol. i. p. 99.

Explanation of Plate 1.

Fig. 1.—Schematic representation of displacement of the auditory ossicles due to contraction of the tensor tympani muscle (Testut): *a*, external auditory meatus; *b*, tympanic cavity; *c*, vestibule of the bony labyrinth; *d*, fenestra ovalis; 1, membrana tympani; 2, handle of malleus; 3, head of malleus; 4, insertion of tendon of tensor tympani; 5, long or vertical process of incus; 6, head of incus; 7, stapes. (The arrow indicates the direction of traction of the tensor tympani muscle; and the lines in red indicate the change in the position of the parts produced by it.)

Fig. 2.—Schematic representation of the displacement of the stapes due to contraction of the stapedius muscle (Testut): *A*, the stapes in repose; *B*, stapes during contraction of stapedius muscle; 1, base of stapes; 2, anterior border of fenestra ovalis; 3, the pyramid; 4, tendon of stapedius muscle; *a*, anterior portion of annular ligament of stapes, longer than *b*, posterior portion of same ligament; *x*, *x*, antero-posterior diameter of fenestra ovalis, passing through the base of the resting stapes; *y*, point of passage of the vertical line which represents the axis of rotation of the stapes.

Fig. 3.—The three parts making up the bony cochlea (schematic, from Testut): *A*, the columella; *B*, spiral tube containing the scalæ; *C*, lamina spiralis; *D*, the three parts in their normal relations.

Fig. 4.—Schematic representation of the perilymphatic and endolymphatic spaces. The former appear in black, and the latter are colored blue (Testut): 1, utricle; 2, saccule; 3, semicircular canal; 4, canalis cochlearis; 5, ductus endolymphaticus with its two branches of origin; 6, saccus endolymphaticus; 7, canalis reuniens, or canal of Hensen; 8, scala tympani; 9, scala vestibuli; 10, their communication at the helicotrema; 11, aquæductus vestibuli; 12, aquæductus cochlearis; 13, periosteum; 14, dura mater; 15, stapes in the fenestra ovalis; 16, fenestra rotunda with its membrane.

represented graphically by depicting under one another a series of waves having two, three, four, etc. times the rate of succession of the curve indicating the fundamental tone. If a vertical line be drawn across the series representing the vibration-rates of the various tones, and an algebraic addition be made of the distance of each point of intersection above or below the line of rest, the result will determine the position of the composite curve on the same vertical (Fig. 196). It is evident that the form of the composite wave must change with every change in the number and relative prominence of musical overtones, and the movement imparted by it to the tympanic membrane and the wave

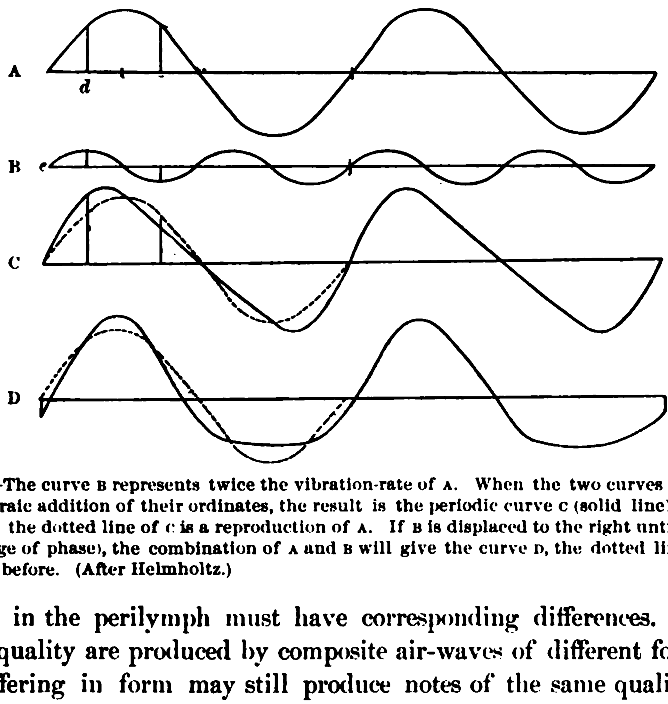


FIG. 196.—The curve B represents twice the vibration-rate of A. When the two curves are combined by the algebraic addition of their ordinates, the result is the periodic curve C (solid line), having a different form; the dotted line of C is a reproduction of A. If B is displaced to the right until *e* falls under *d* in A (change of phase), the combination of A and B will give the curve D, the dotted line in D representing A as before. (After Helmholtz.)

generated in the perilymph must have corresponding differences. Notes of different quality are produced by composite air-waves of different forms. But waves differing in form may still produce notes of the same quality; for if, in the graphical figure, one or more of the curves representing simple tones be slid to the right or the left, the form of the composite wave will thereby be changed, but not the quality of the sound produced by it. In other words, change of phase of the partial tones does not alter the quality of the note.[1] The quality of any complex note may be reproduced by sounding together a series of tuning-forks which have, respectively, the vibration-rate of the fundamental tone and that of one of the overtones of the complex note.

Analysis of Composite Tones by the Ear.—According to the theory outlined on page 380, the composite wave, beating against the sensitive organ of the cochlea, is again analyzed into the elements composing it, one part of the basilar membrane vibrating sympathetically with one partial tone, another with another. The isolated irritation of each nerve-element arouses in the mind the idea of a tone of a certain pitch and loudness; but when a number

[1] Helmholtz, *op. cit.*, pp. 30-34.

IV. PHYSIOLOGY OF SPECIAL MUSCULAR MECHANISMS.

A. The Action of Locomotor Mechanisms.

The Articulations.—The form, posture, and movements of vertebrates are largely determined by the structure of the skeleton and the method of union of the bones of which it is composed. There are two hundred bones in the human skeleton, and they are so connected together as to be immovable, or to allow of many varieties and degrees of motion. There are four principal methods of articulation:

1. **Union by Bony Substance (Suture).**—This form of union occurs between the bones of the skull. These bones, which at birth are independent structures connected by fibrous tissue, gradually grow together and make a continuous whole, only a more or less distinct seam remaining as witness of the original condition.

2. **Union by Fibro-Cartilages (Symphysis).**—The bodies of the vertebræ and the sacro-iliac and pubic bones are closely bound together by disks of fibro-cartilage. This material, which is very strong, but yielding and elastic, acts as a buffer to deaden the effect of jars, permits of a slight amount of movement when the force applied is considerable, and restores the bones to their original position on the removal of the force. The spinal column can be thought of as an elastic staff; the capacity for movement differs greatly in different regions, however, partly on account of differences in the thickness of the intervertebral disks as compared with the antero-posterior and lateral diameters of the bodies of the vertebræ, and more especially on account of the method of contact of the superior and inferior vertebral processes. In the cervical region the disks are thick and the diameter of the vertebræ is small, and this permits of considerable bending in all directions and a certain amount of rotation. In the dorsal region a slight amount of bending from side to side and a slight amount of rotation are possible; but backward bending is inhibited by contact of the articular processes, and forward bending is prevented by the strong articular ligaments. In the lumbar region bending in all directions is more free, but rotation is made impossible by the interlocking of the articular processes.[1]

3. **Union of Fibrous Bands (Syndesmosis).**—Some of the bones, as those of the carpus and tarsus, are connected by interosseous ligaments which, at the same time that they bind the bones together, admit of a certain amount of

[1] Fick: *Compendium der Physiologie des Menschen*, Wien, 1891.

group 2. They may be divided into *labio-dental frictionals*, *f* (without voice); *v*, *w* (with voice); the *lingual frictionals* *s*, *th* (as in *them*); *sh*, *ch* soft (without voice); *z*, *j* (with voice). The sound of *h* may be regarded as due to the vibration of the separated vocal cords. It is peculiar, however, in appearing to be formed in any part of the vocal chamber; when it is formed the mouth parts take on no peculiar position, but assume that of the vowel following the *h*, as *hark*, *hear*, etc.

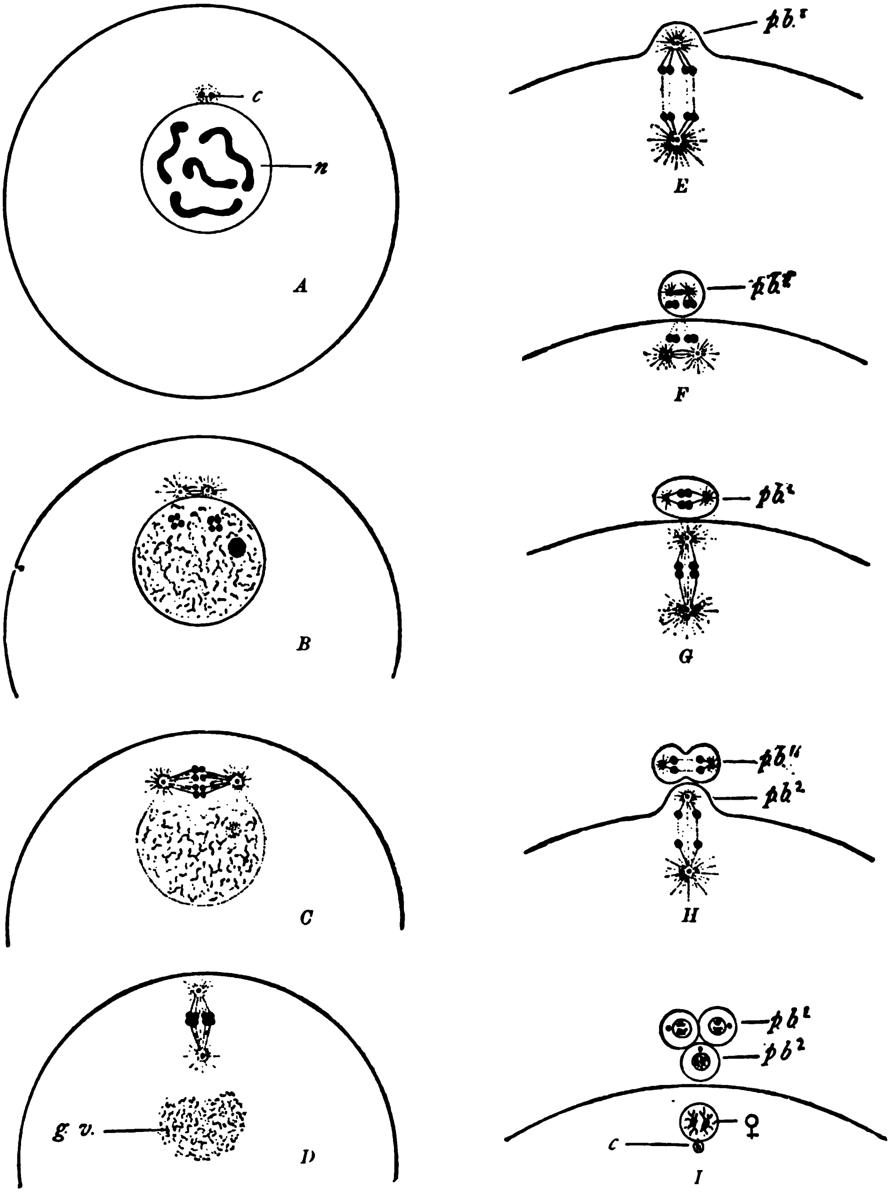


FIG. 221.—Stages in the maturation of the ovum; diagrammatic (mainly from Wilson): *A*, the original ovarian ovum; *n*, its nucleus, containing four chromosomes; *c*, its double centrosome, surrounded by the attraction sphere; in *B* much of the chromatin has begun to degenerate; the rest has become arranged into two quadruple groups of chromosomes, or tetrads; the formation of the spindle and the asters has begun; in *C* the first polar amphiaster, bearing the chromosomes, is completed; in *D* the amphiaster has become rotated and has travelled toward the surface of the ovum; *g. v*, the degenerated remains of the nucleus; in *E* the division of the tetrads into double groups of chromosomes, or dyads, has begun, and the first polar body, *p. b*¹, is indicated; in *F* the first polar body, containing two dyads, has been extruded; the formation of the second polar amphiaster has begun; in *G* the first polar body is preparing to divide; the second polar amphiaster is fully formed; in *H* the division of the dyads into single chromosomes in both the first polar body and the egg has begun, and the second polar body, *p. b*², is indicated; in *I* the formation of the polar bodies is completed; ♀, the egg-nucleus, containing two small chromosomes, one-half the original number. In fertilization the spermatozoon will bring in two additional chromosomes, thus restoring the total number of four.

more hypotheses, bearing upon the determination of sex, have been brought forward. The Hofacker-Sadler law (Hofacker, 1828; Sadler, 1830) is well known, as follows: If the father be older than the mother, more boys than girls will be born; if the parents be of equal age, slightly more girls than boys; if the mother be older than the father, the probability of girls is still greater. Since the promulgation of this so-called law facts for and against it have been brought forward, but the balance of evidence seems to be in favor of its truth. Thury in 1863 claimed that the degree of "ripeness" of the ovum is the determining factor—the female resulting from the less ripe ovum, hence the earlier after its liberation the egg is fertilized, the greater is the tendency to the production of a female; the later the fertilization, the greater the probability of a male. While it is not at all clear in what the "ripeness" or "unripeness" of an ovum consists, breeders have made use of this principle apparently with success—offspring conceived at the beginning of "heat" seem to be more usually females. Likewise, it is frequently believed that in human beings conceptions immediately after menstruation produce a larger proportion of females than later conceptions. Schenk[1] also bases his view on the condition of ripeness of the ovum. He regards the presence of sugar in the urine of the pregnant woman as evidence of incomplete metabolism in the body, thus of incomplete nutrition or unripeness of the ovum, and hence of tendency toward femaleness in the offspring. By means of a highly nitrogenous diet, which eliminates the sugar from the urine and increases the proportion of reducing substances, he claims to make the metabolism more complete, to insure a riper ovum, and hence to make it probable that the offspring will be a male. Schenk's reasoning is excessively hypothetical, and his present facts are too few to substantiate his claims. Düsing[2] accepts Thury's view and extends it to the male element—the younger the spermatozoon the greater the tendency toward the production of males. Hence among animals the scarcity of one sex leads to the more frequent exercise of its reproductive function, the employment of younger germ-cells, and therefore the relative increase of that sex. Further, the nearer a parent is to the height of his reproductive capacity the less will be the probability of transmitting his own sex to the offspring. Nutrition seems to have some obscure relation to the question of sex. Thus, by feeding tadpoles with highly nutritious flesh Yung[3] increased the percentage of females from 56 to 92. Mrs. Treat[4] showed that the butterflies of well-fed caterpillars became females, those of starved caterpillars males. Statistics among mammals and human beings indicate that the proportion of male to female offspring varies inversely with the nutrition of the parents, especially of the mother. Thus,

[1] L. Schenk: *Einfluss auf das Geschlechtverhältniss*, Magdeburg, 1898. Authorized translation: *The Determination of Sex*, London, 1898.

[2] K. Düsing: *Jenaische Zeitschrift für Naturwissenschaft*, 1883, xvi., and 1884, xvii.; also published separately, *Die Regulierung des Geschlectverhältnisses bei der Vermehrung der Menschen, Tiere und Pflanzen*, Jena, 1884.

[3] E. Yung: *Comptes rendus de l'académie des sciences*, Paris, 1881, xcii.

[4] Mrs. Mary Treat: *The American Naturalist*, 1873, vii.

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